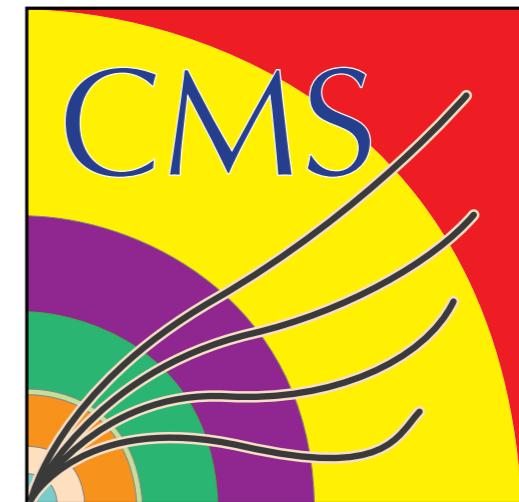


A Discovery in the Search for the Elusive Higgs Boson at CMS

Andrei Gritsan

Johns Hopkins University

for the CMS Collaboration



9 July 2012

Fermilab

Joint Experimental-Theoretical Seminar

Why Search for the Higgs Boson

- we know 12 bosons: γ , Z^0 , W^+ , W^- , 8 gluons

– carry force, spin= $\hbar=1$

- in early Universe: all massless, forces unify

- as Universe cools down

– symmetry spontaneously breaks

$$|\gamma\rangle = \cos\theta_W|B^0\rangle + \sin\theta_W|W^0\rangle \quad \text{light}$$

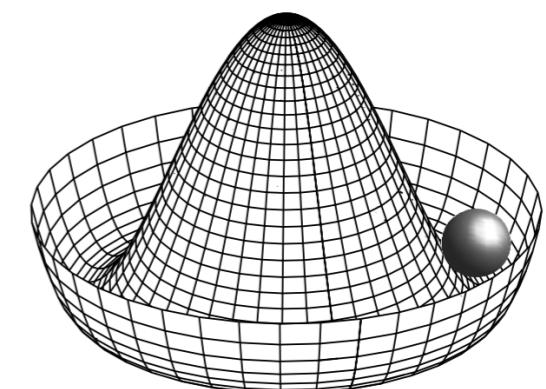
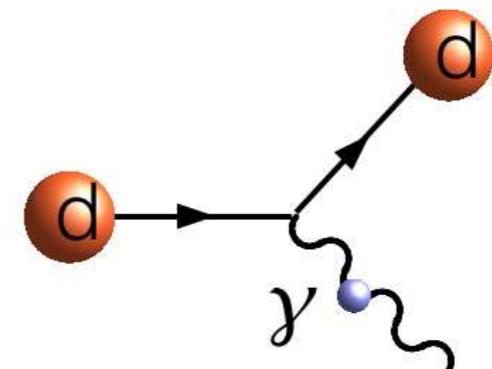
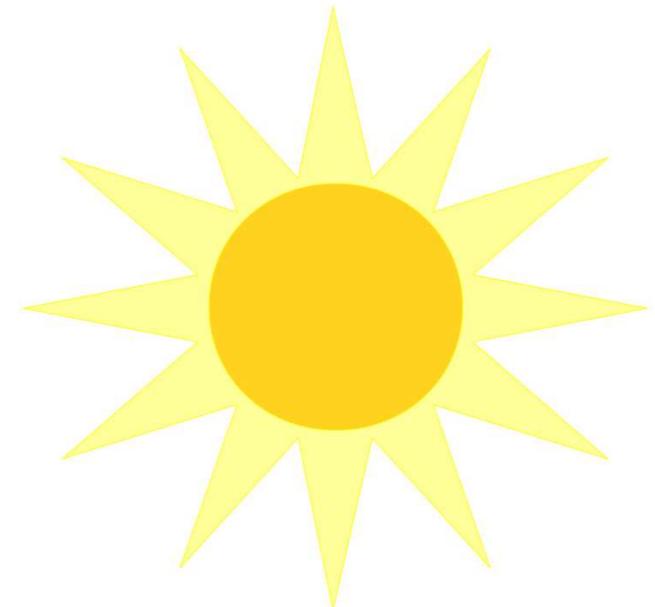
$$|Z^0\rangle = \sin\theta_W|B^0\rangle + \cos\theta_W|W^0\rangle \quad \text{heavy}$$

– weak interactions become weak (Z^0 , W^\pm mass)

– Higgs field in vacuum – possible mechanism

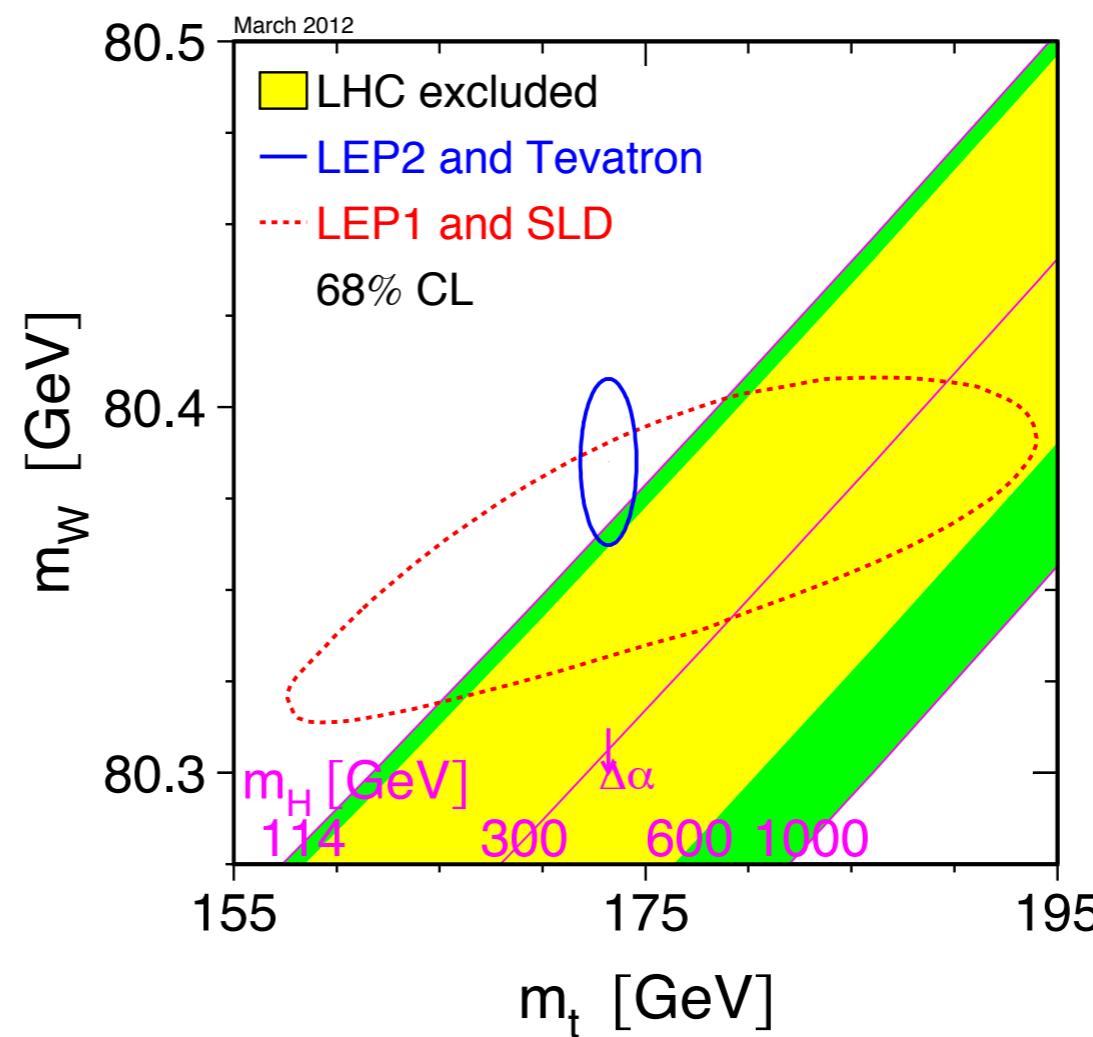
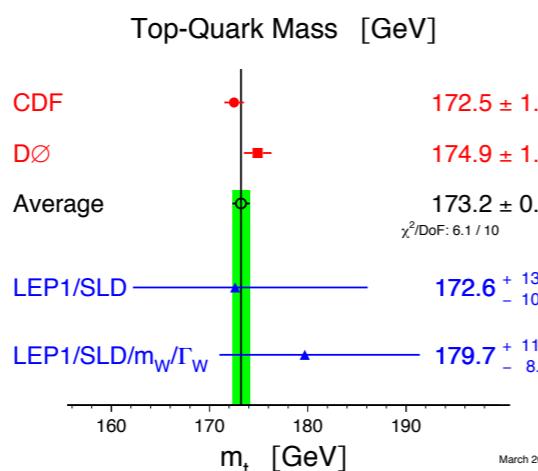
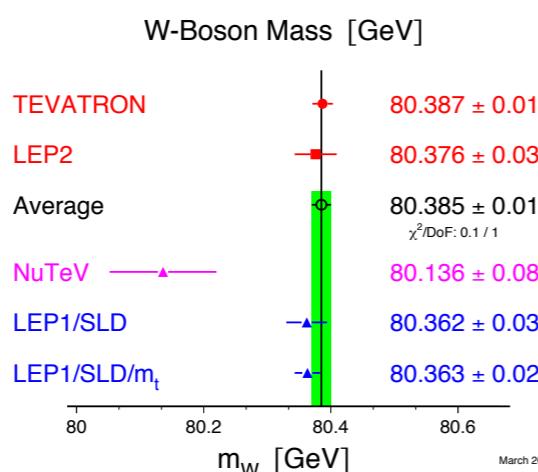
⇒ look for its excitation, the Higgs boson

- is vacuum stable ⇒ fate of the Universe?



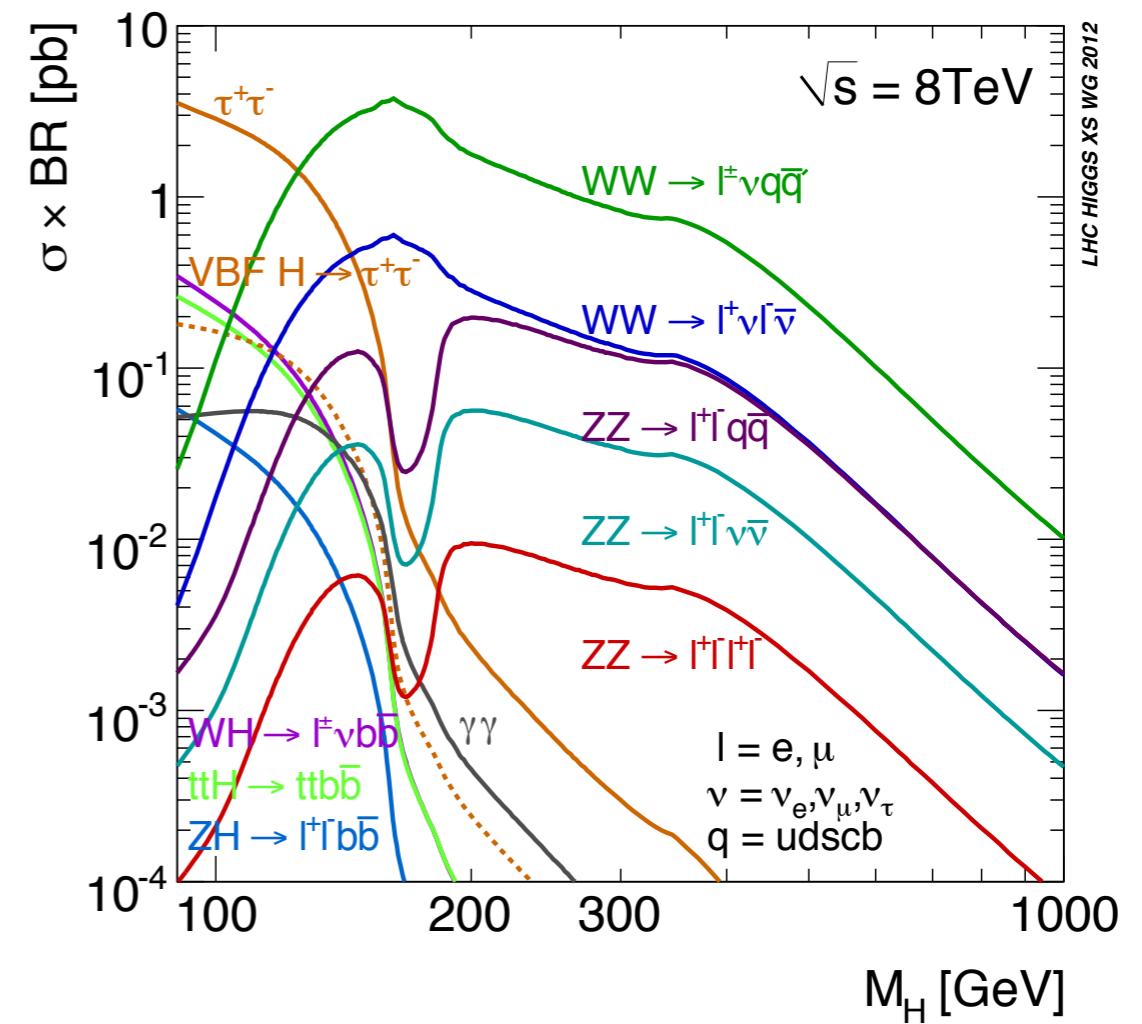
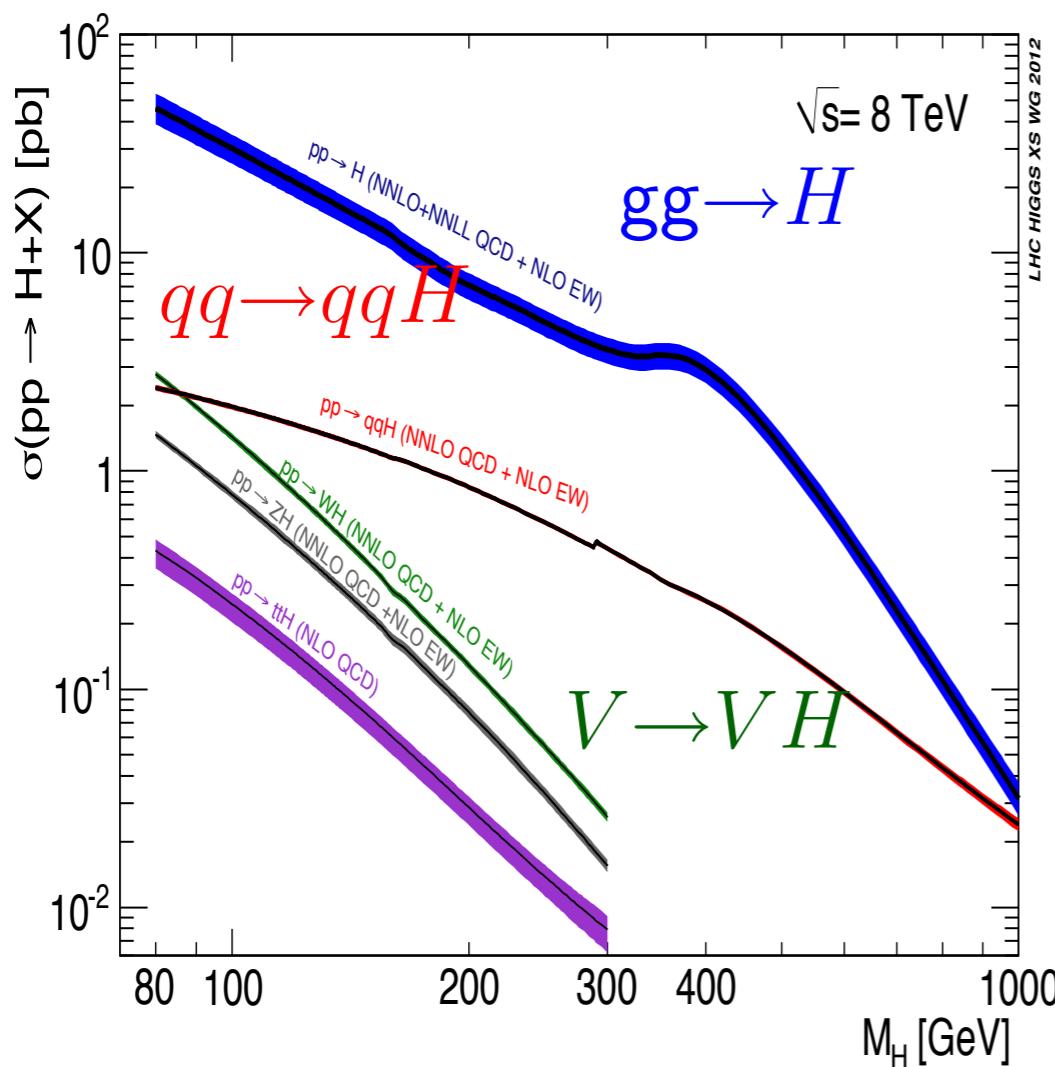
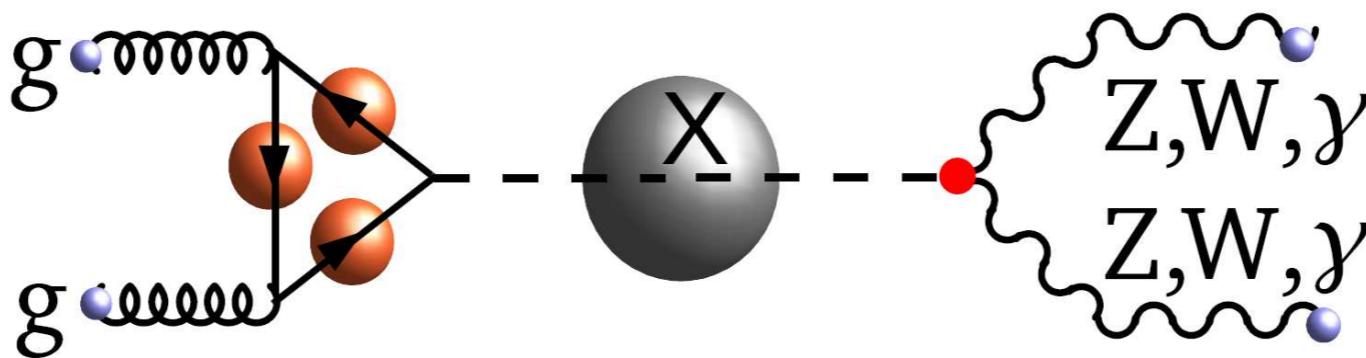
Constraints on the SM Higgs Boson

- SM Higgs boson mass m_H unknown; constraints:
 - indirectly due to m_W , m_t at Tevatron, LEP/SLD
 m_W related to m_t (quadratic) and m_H (log) from loop corrections
 - directly due to LHC, LEP, Tevatron
open $115 < m_H < 127$ GeV



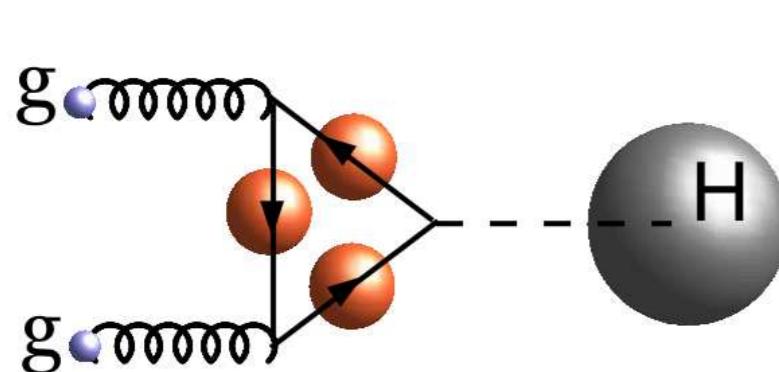
The Hunt for the Higgs Boson

- Excite vacuum: $gg, VBF, \dots \rightarrow H \rightarrow ZZ^{(*)}, WW^{(*)}, \gamma\gamma, \tau^+\tau^-, b\bar{b}, \dots$

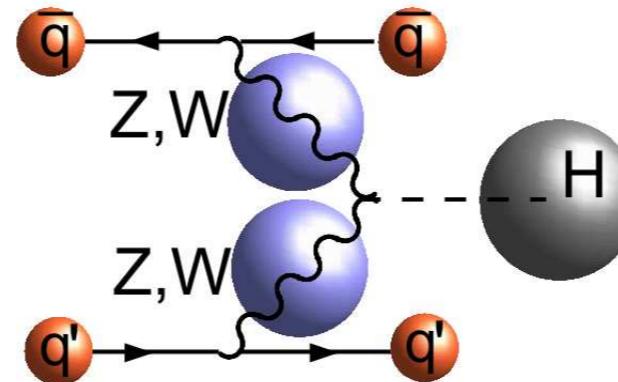


The Challenge is Background

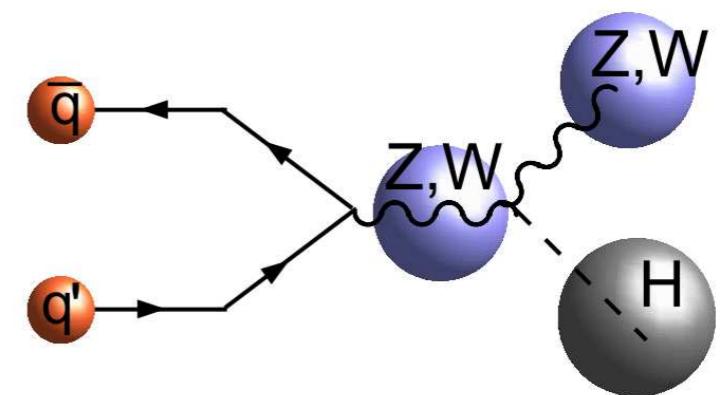
- At LHC might have produced > 100000 Higgs bosons / experiment
gluon fusion



weak boson fusion

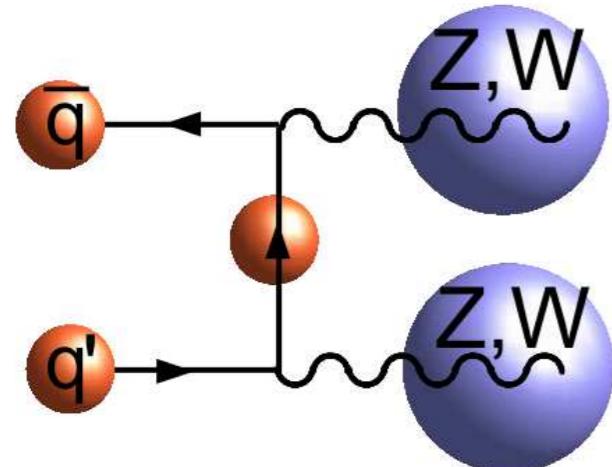


associated production

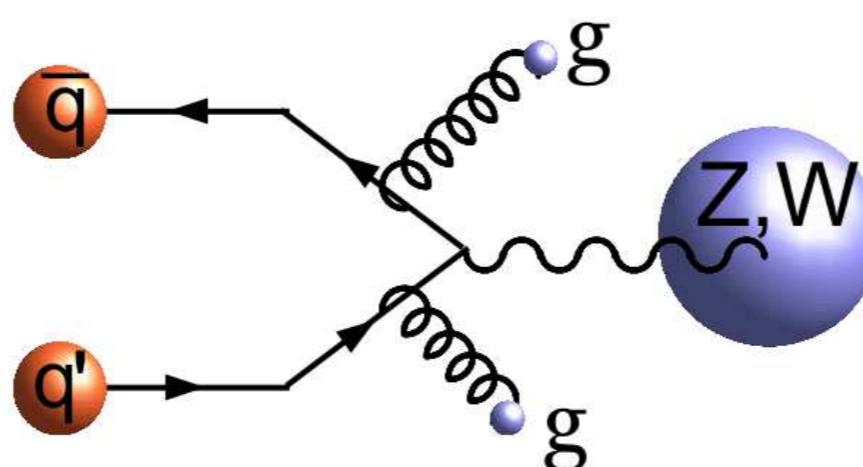


- The challenge is to distinguish **signal** from **backgrounds**, examples:

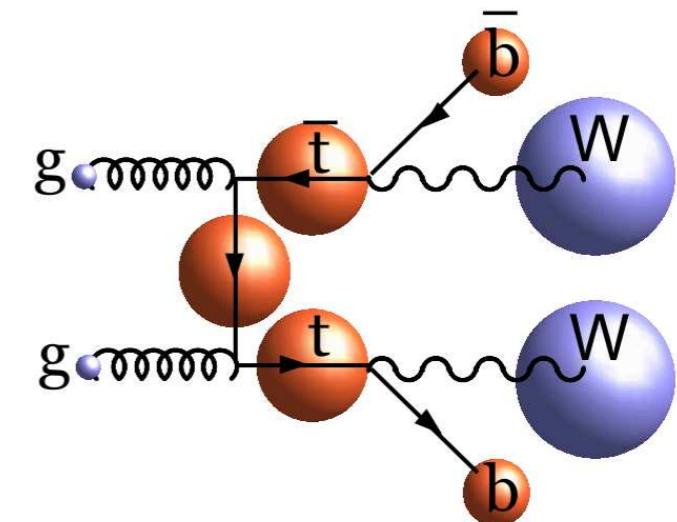
$$q\bar{q} \rightarrow ZZ^{(*)}(\gamma^{(*)})$$



$$q\bar{q} \rightarrow Z(\gamma) + \text{jets}$$

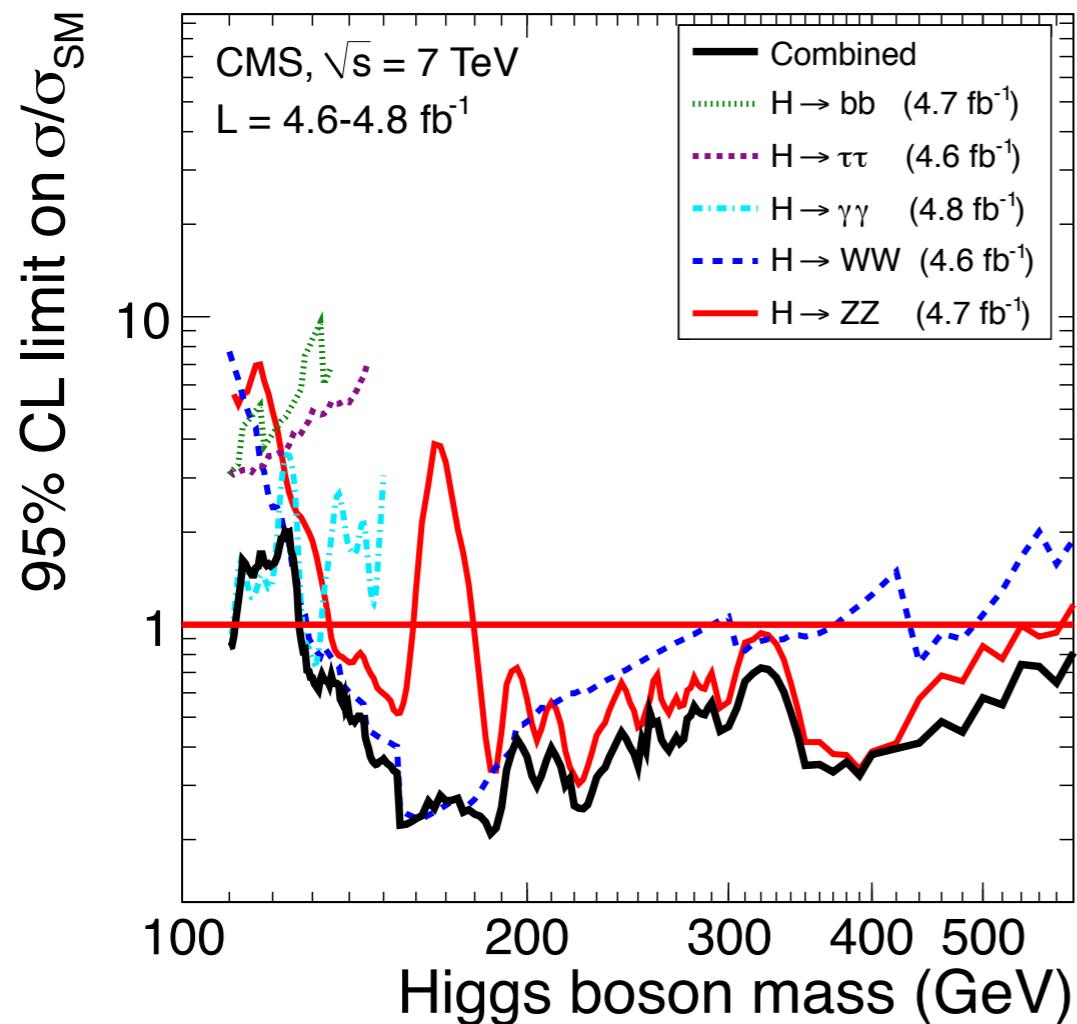


$$gg \rightarrow t\bar{t}$$

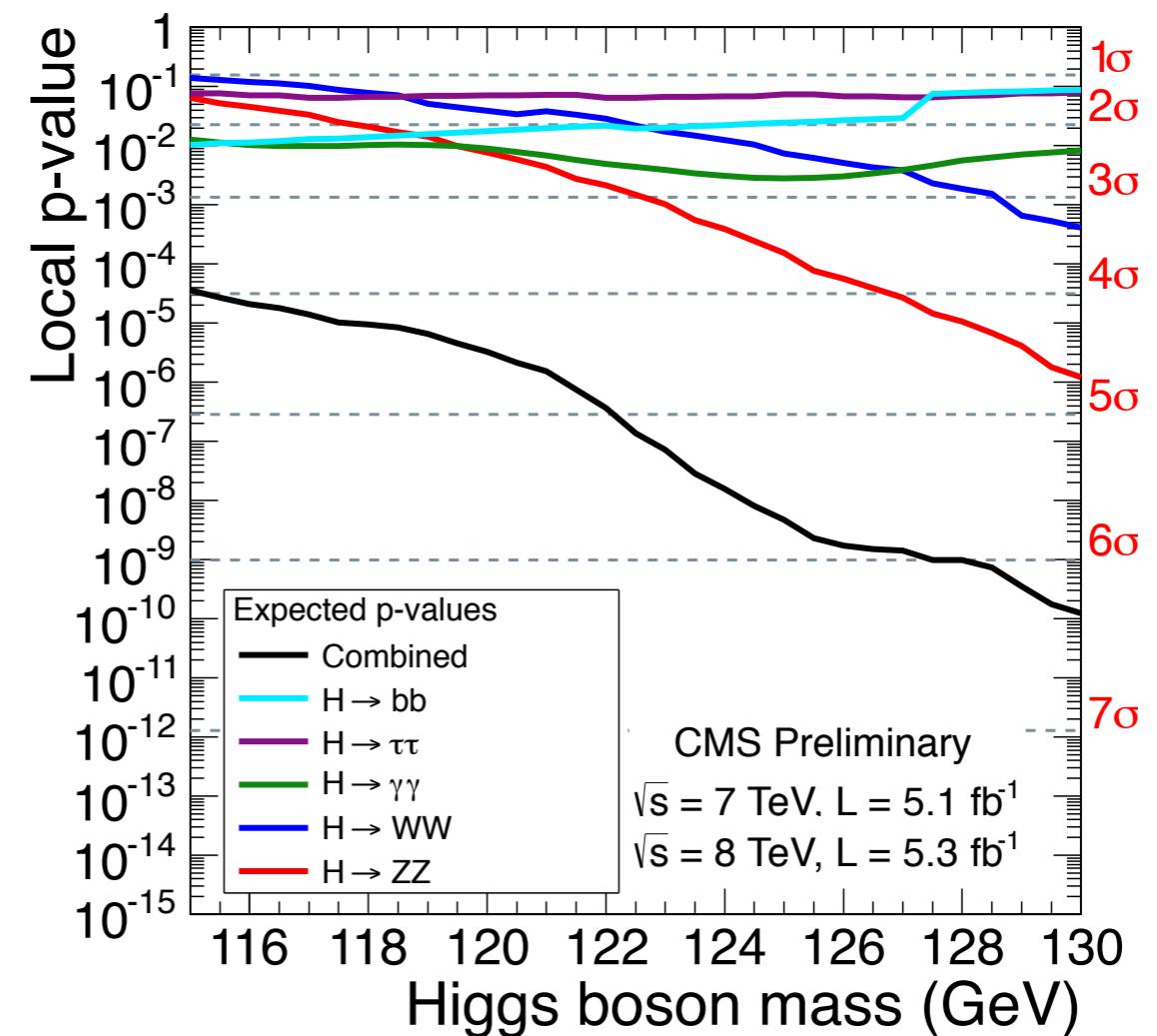


CMS on Track for Discovery

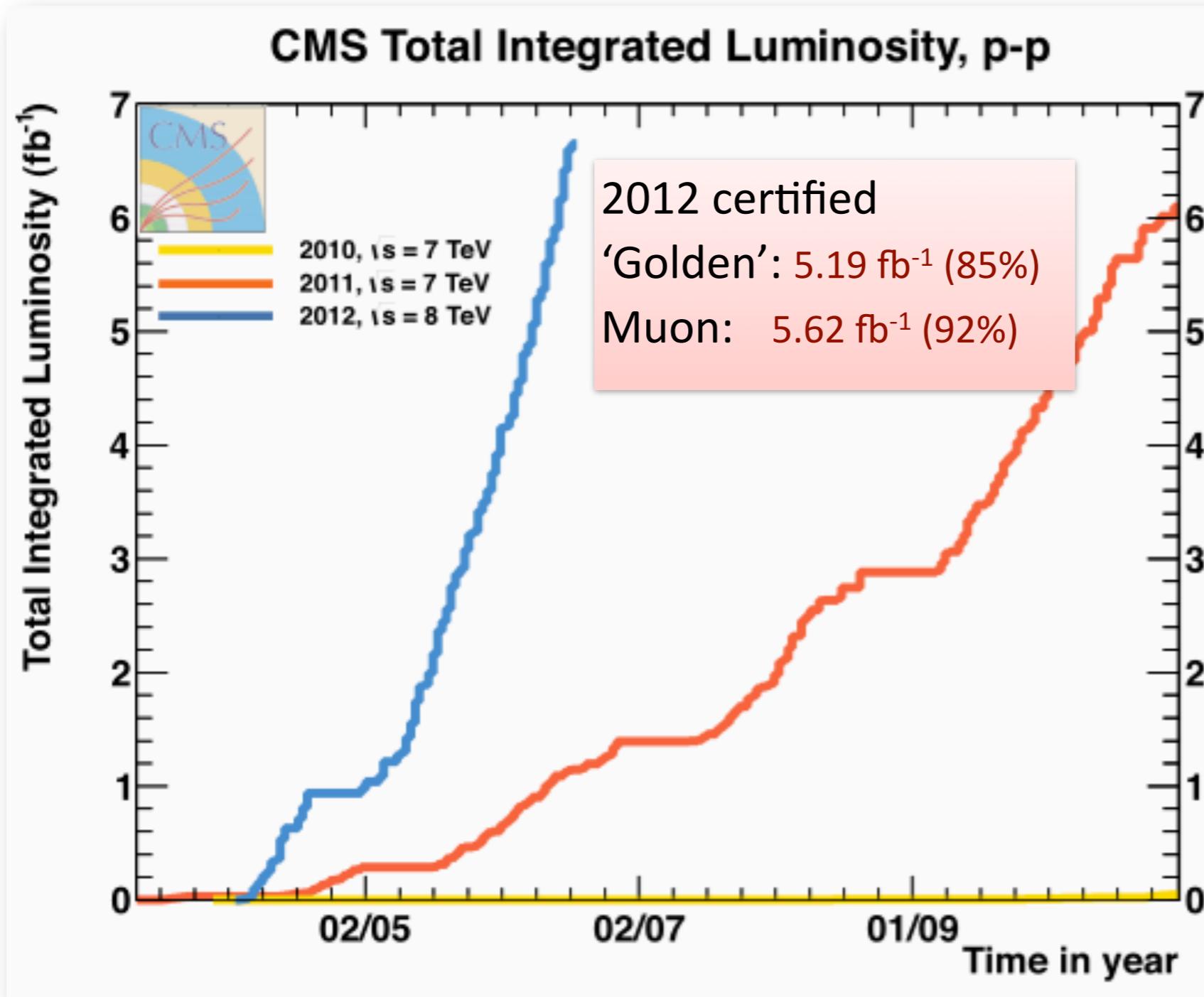
- In December 2011
excluded SM Higgs
 $127 < m_H < 600$ GeV
tantalizing hint $m_H \sim 125$ GeV



- In July 2012
expect for SM Higgs
up to 6σ observation
 $H \rightarrow ZZ^{(*)}, \gamma\gamma, WW^{(*)}, b\bar{b}, \tau\tau$



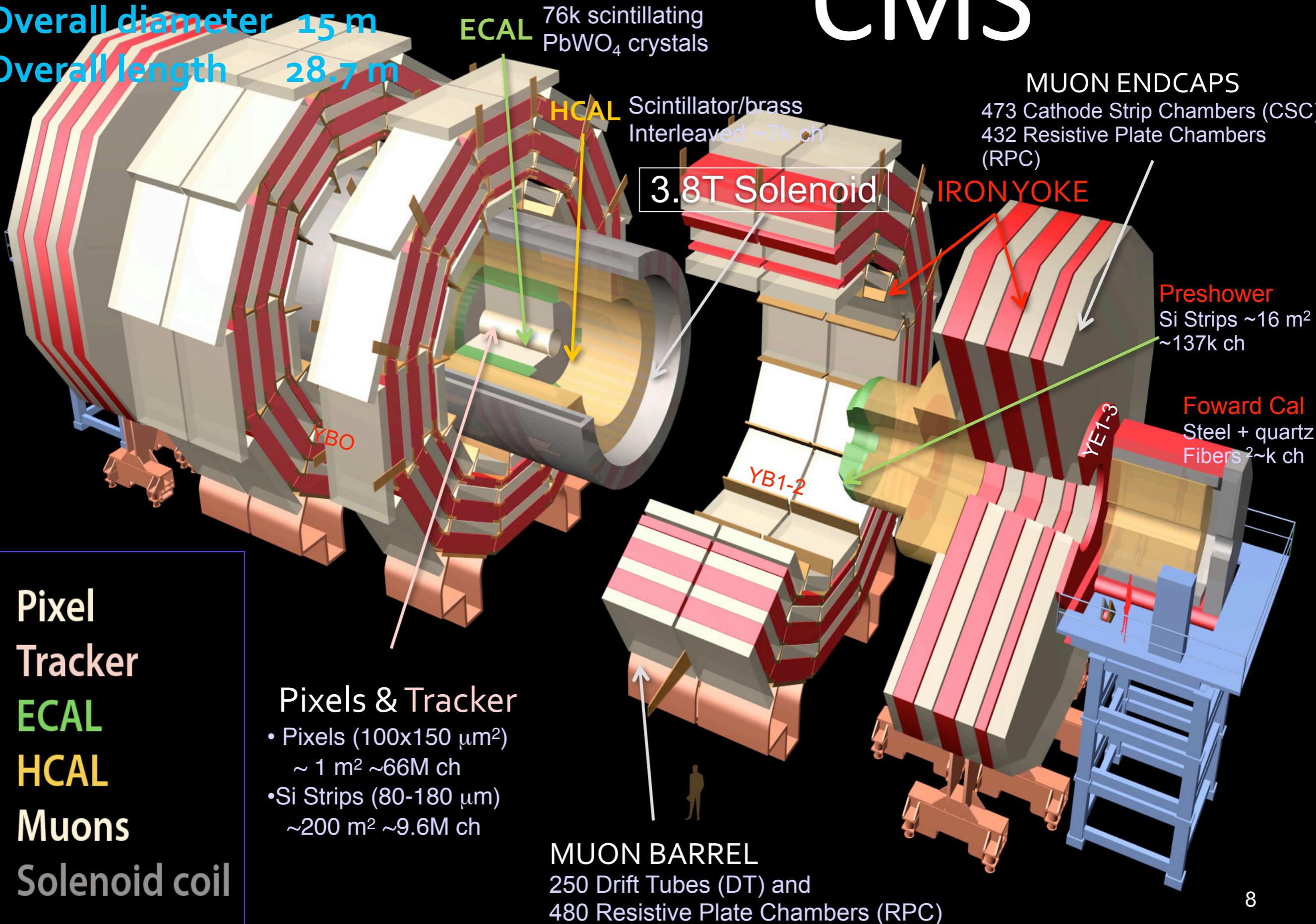
Thanks to excellent LHC performance



Excellent performance of the LHC

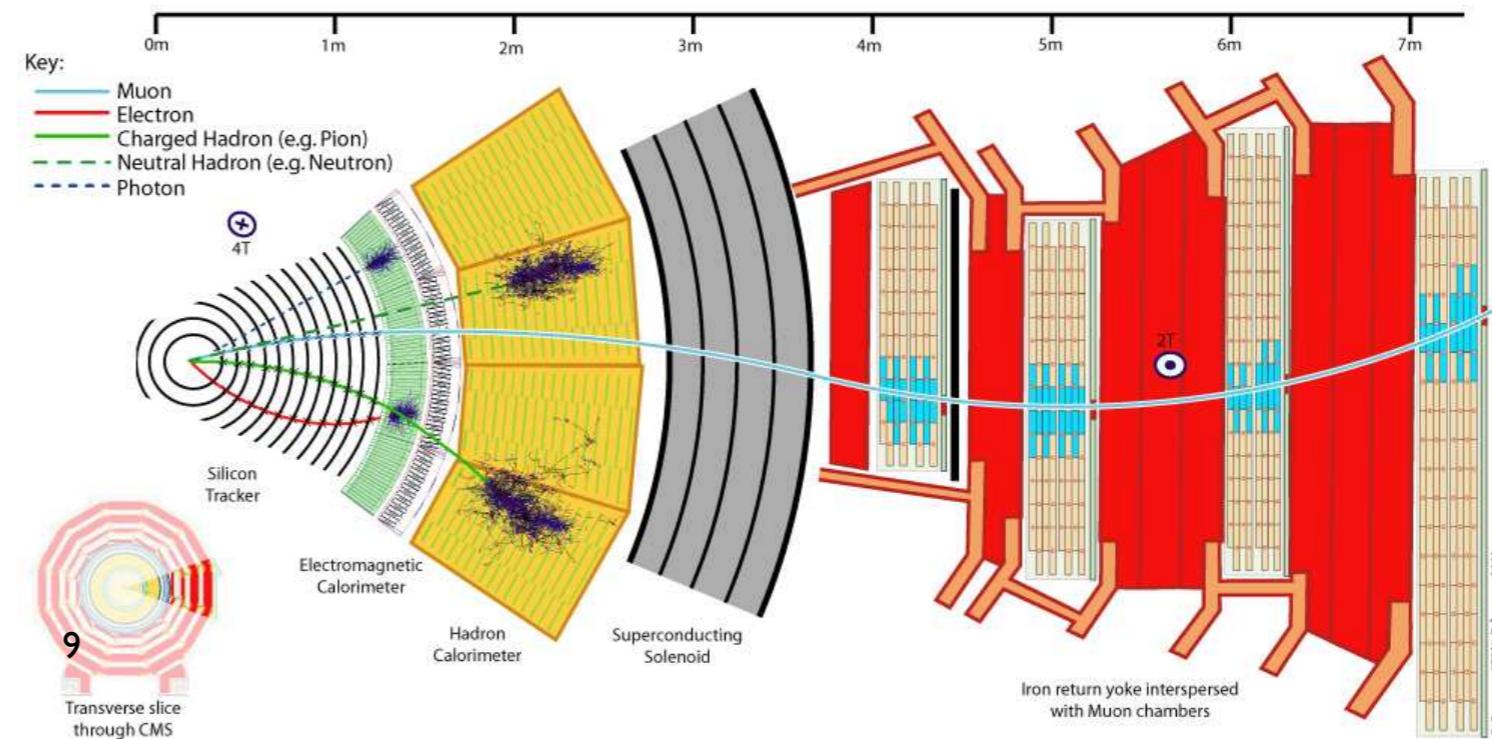
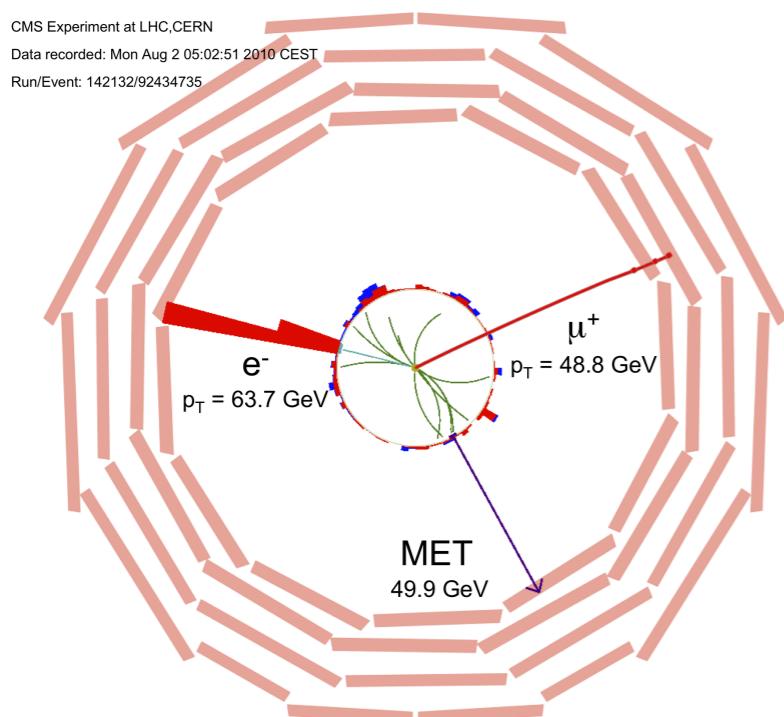
CMS

Total weight **14000 t**
 Overall diameter **15 m**
 Overall length **28.7 m**



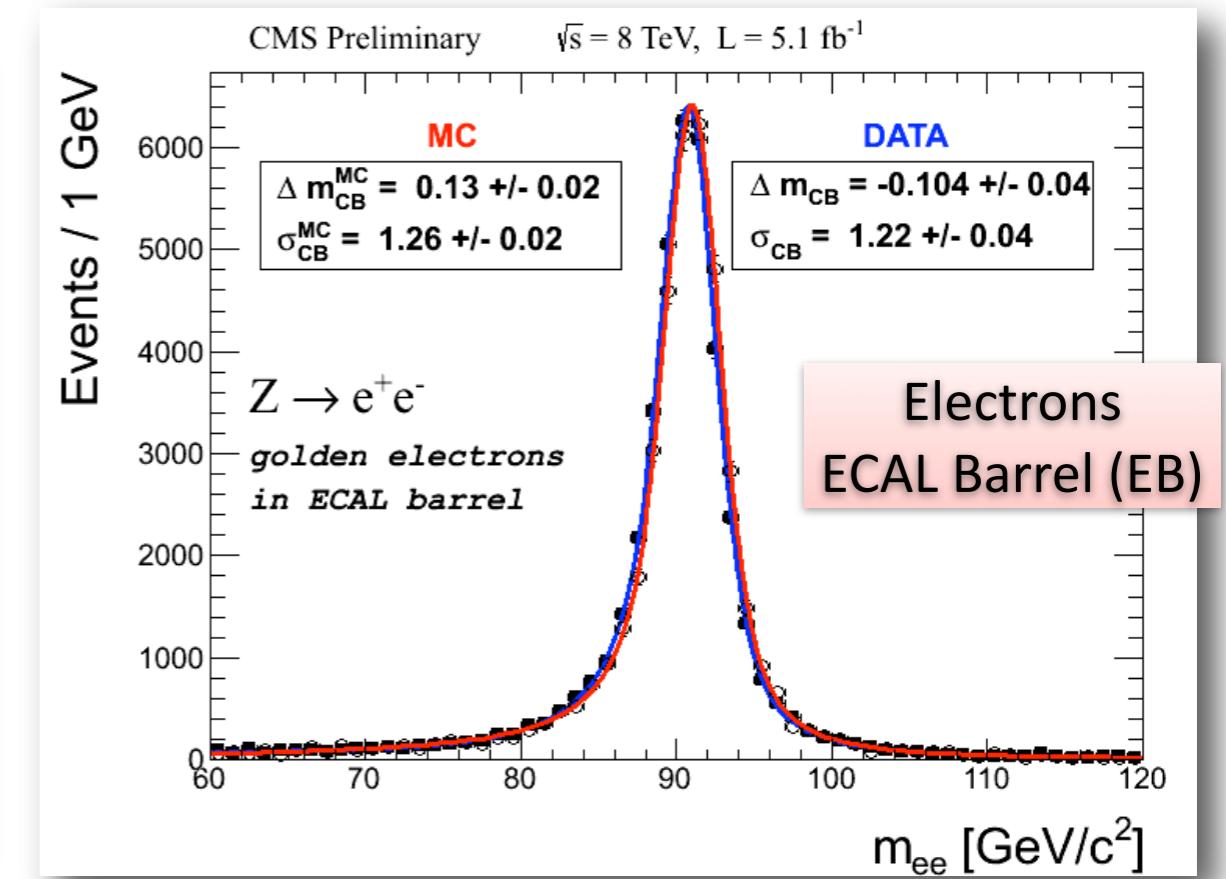
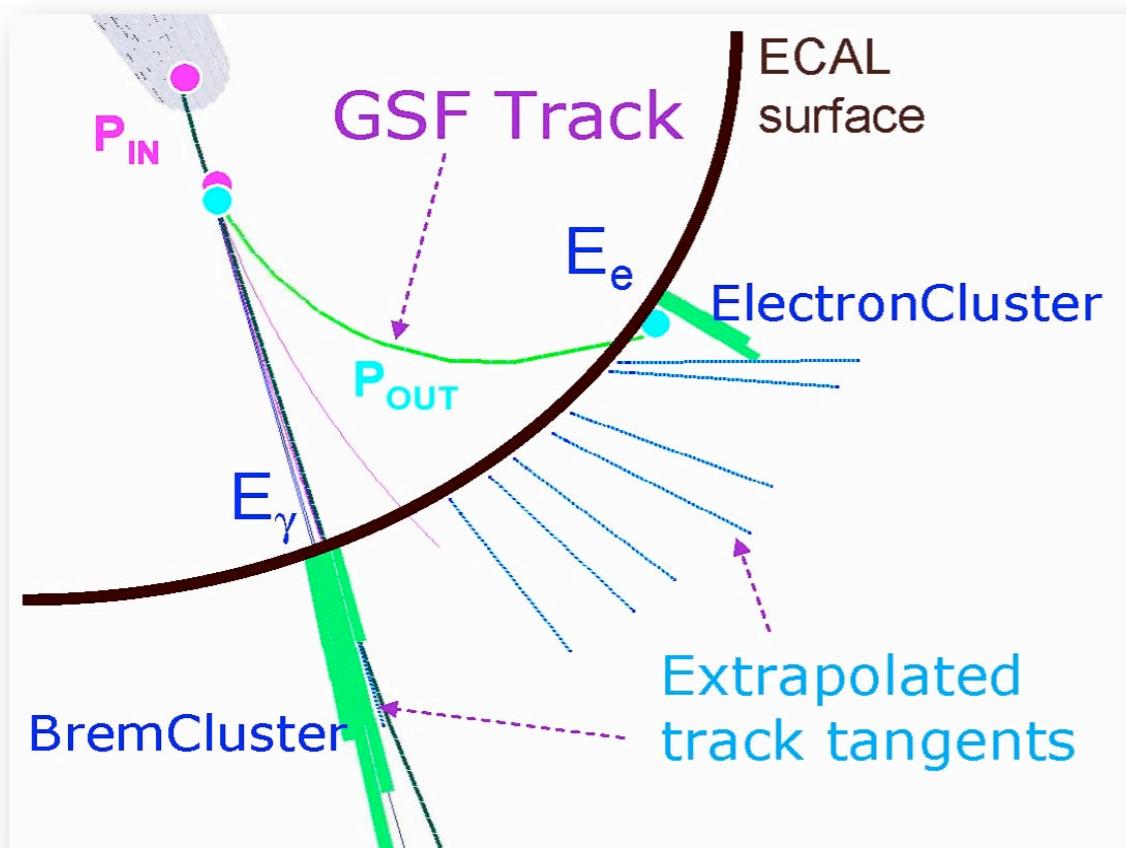
Global Event Description: Particle Flow

- Leptons: ℓ^\pm in Si Tracker: e^\pm (EM Calorimeter), μ^\pm (Muon System)
- Photons: γ (EM Calorimeter)
- Charged and neutral hadrons thru Hadronic Calorimer
- Build jets, τ , MET; use in isolation and pileup correction



$$WW \rightarrow (e^- \bar{\nu})(\mu^+ \nu)$$

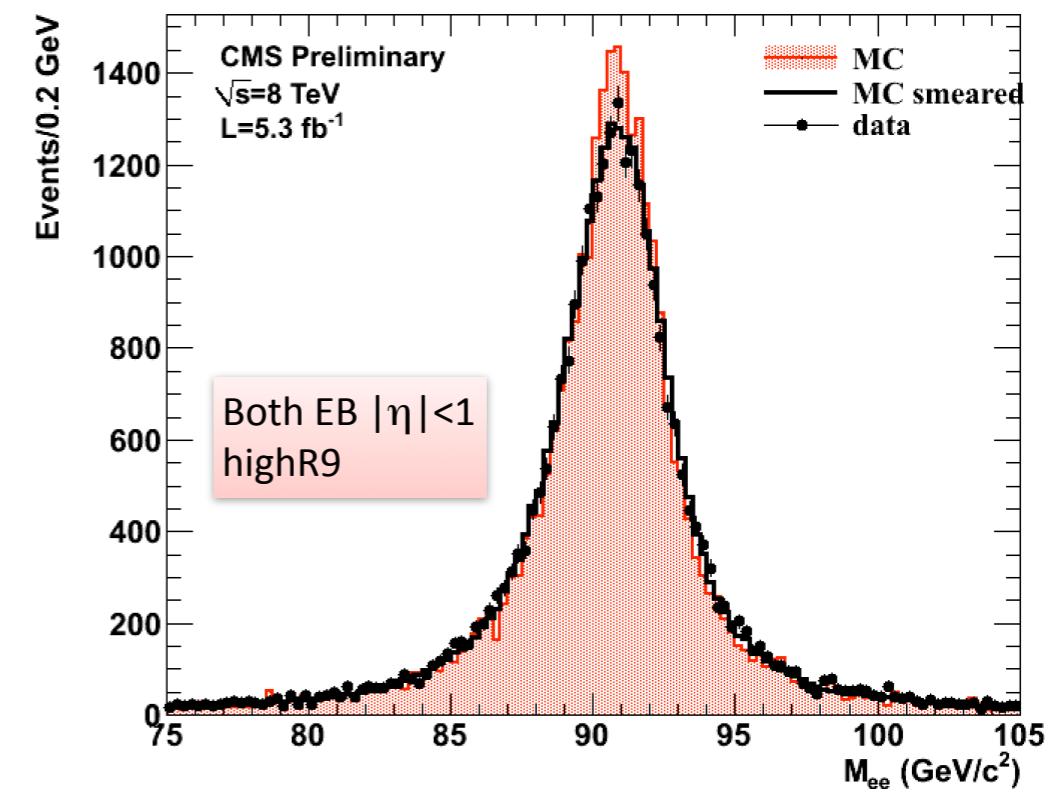
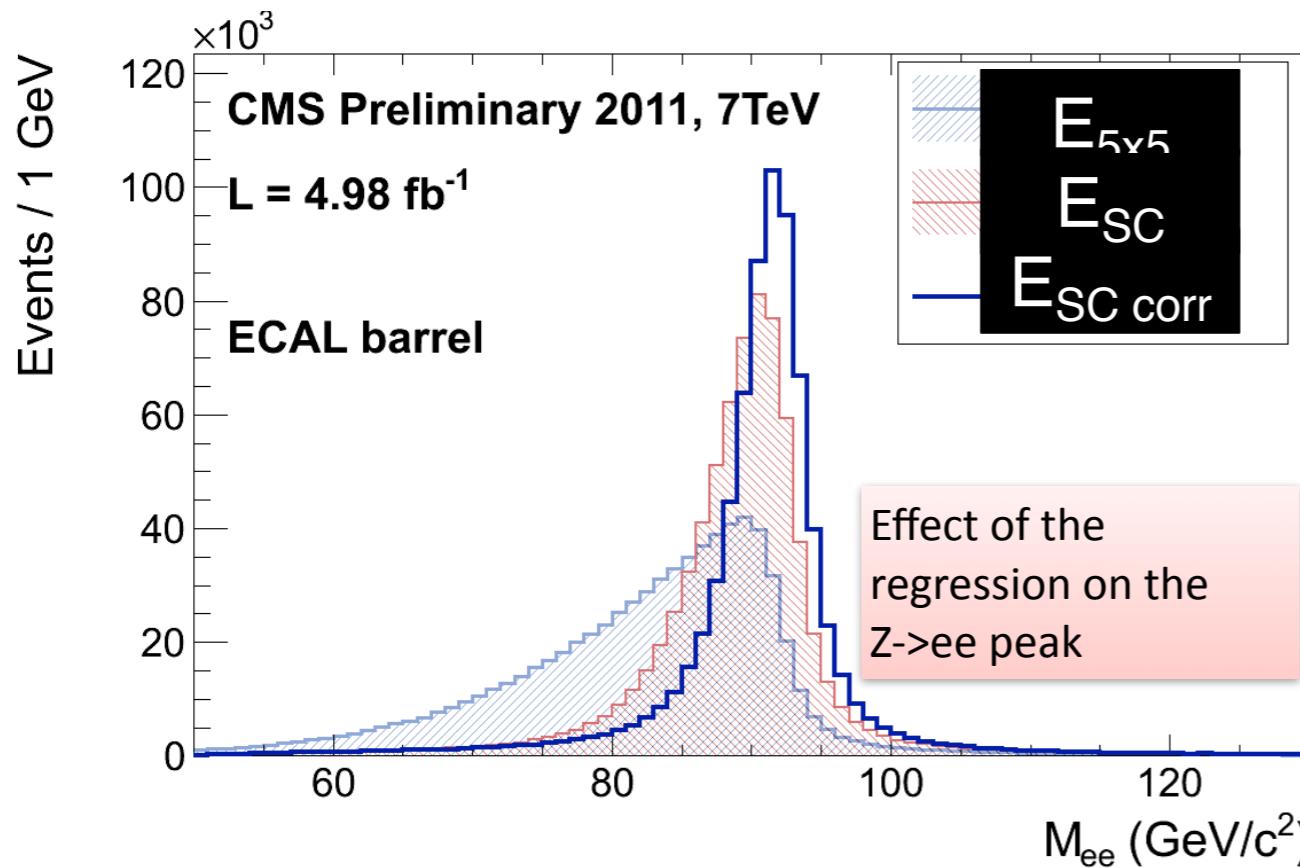
Electron/Photon reconstruction



- Cluster reconstruction in ECAL
 - Common for both electrons and photons (Electrons also reconstructed as photons)
 - Designed to collect bremsstrahlung and conversions in extended phi region
- Dedicated track reconstruction for electrons
 - Gaussian Sum Filter allows for tracks w/large bremsstrahlung
- Photon identification specific to $H \rightarrow \gamma\gamma$

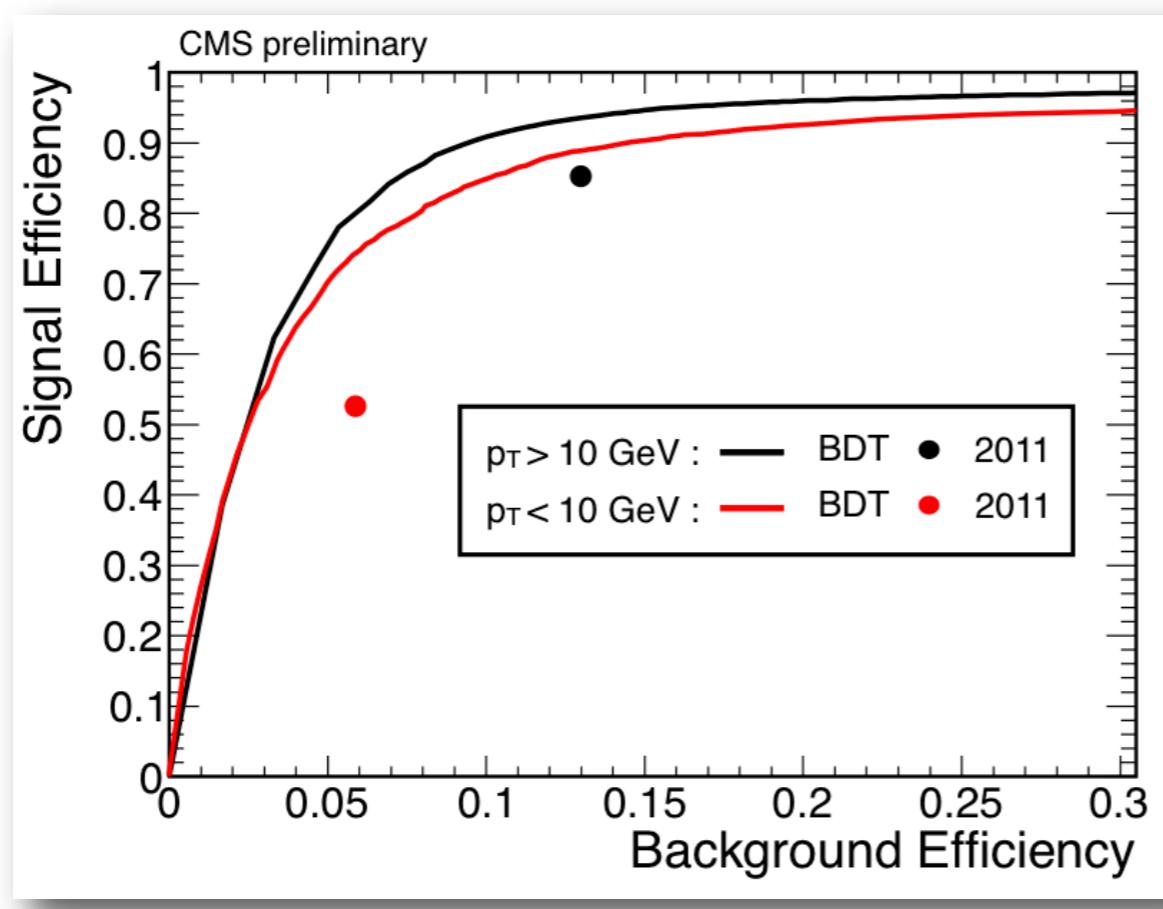
Photon Energy Scale and Resolution

- ECAL cluster energies corrected using a MC trained multivariate regression
 - Improves resolution and restores flat response of energy scale versus pileup
 - Inputs: Raw cluster energies and positions, lateral and longitudinal shower shape variables, local shower positions w.r.t. crystal geometry, pileup estimators
- Regression also used to provide a per photon energy resolution estimate
- To measure the Energy Scale and resolution: use $Z \rightarrow e^+e^-$



Electron identification

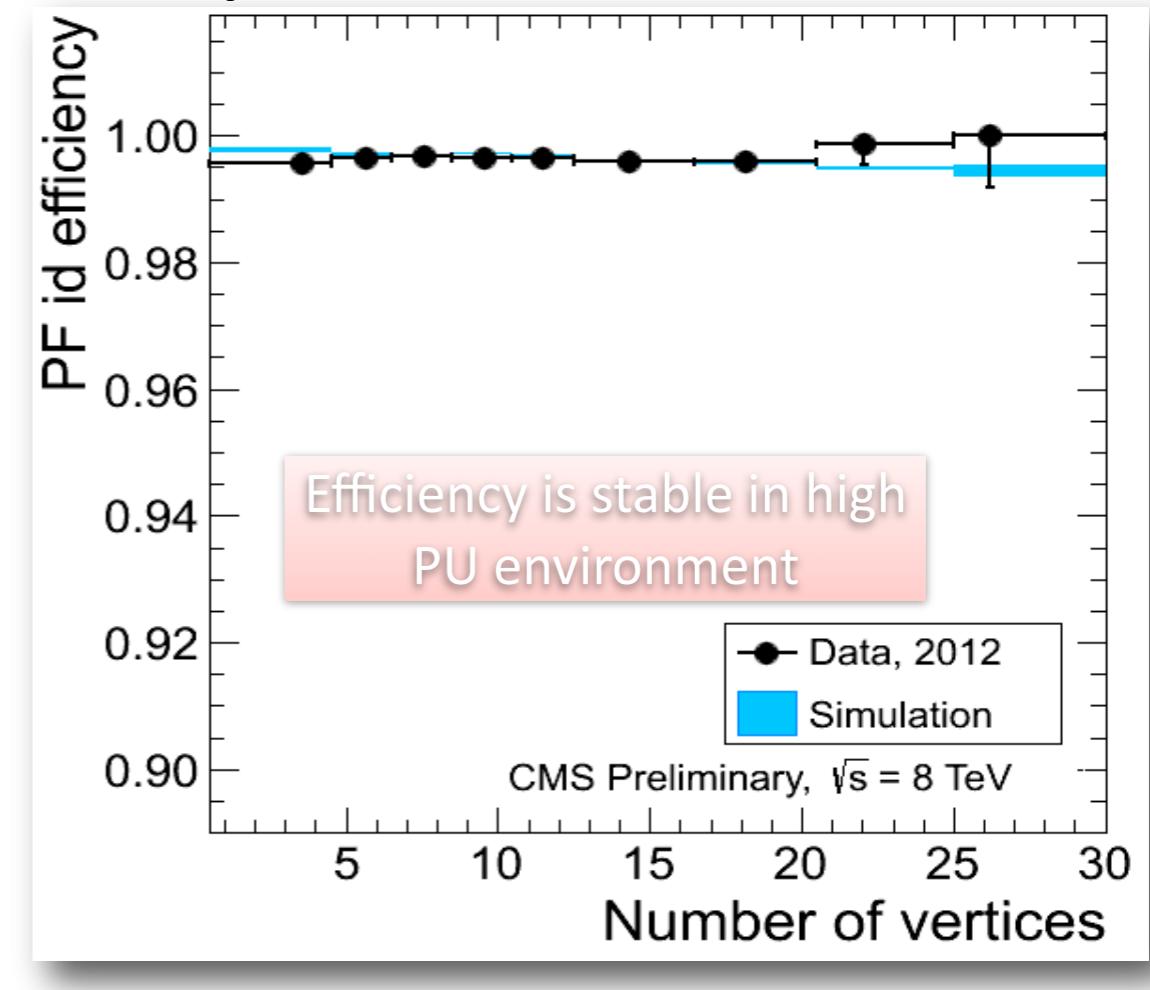
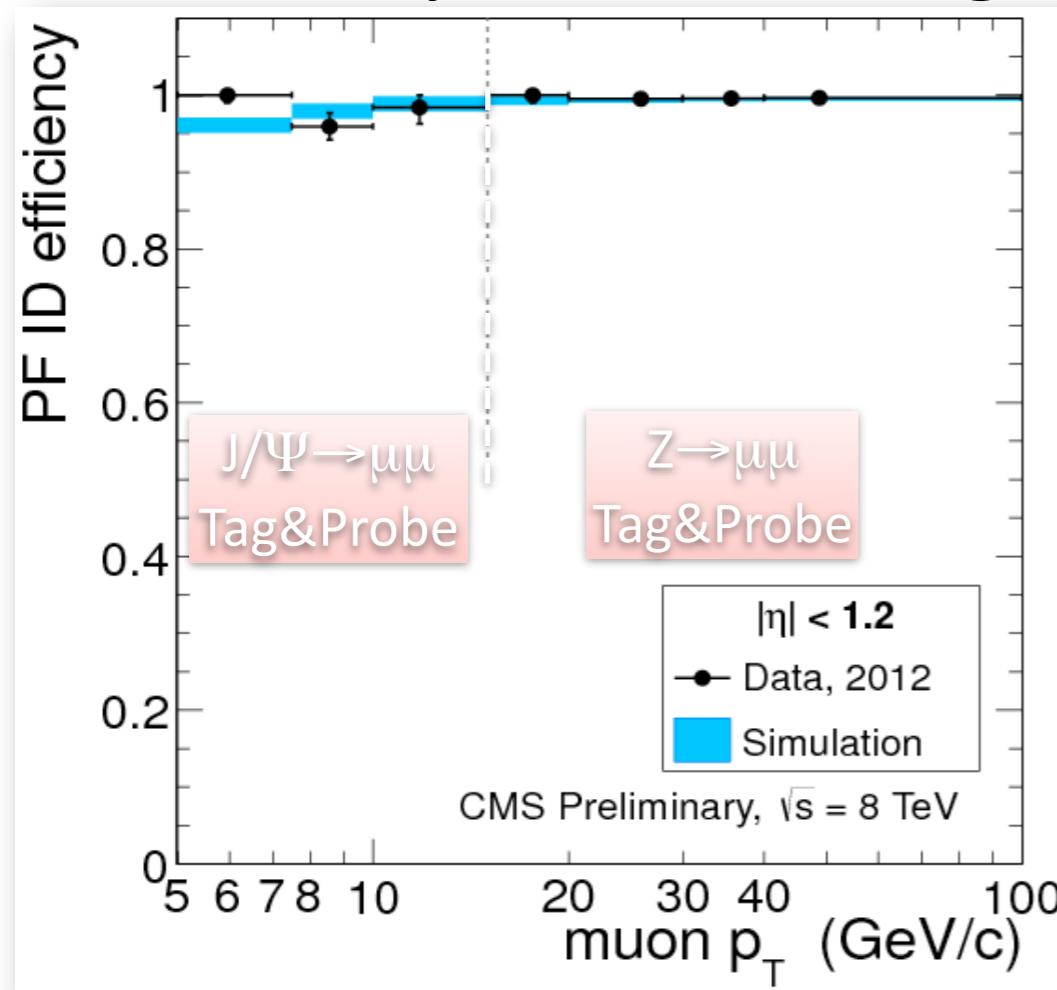
- Multivariate e identification in 2012
 - ECAL, tracker, ECAL-tracker-HCAL matching, impact parameter
 - 30% efficiency improvement in $H \rightarrow ZZ \rightarrow 4e$ wrt cut based ID
- Multivariate training against background in data



Cut Based vs
MVA ID

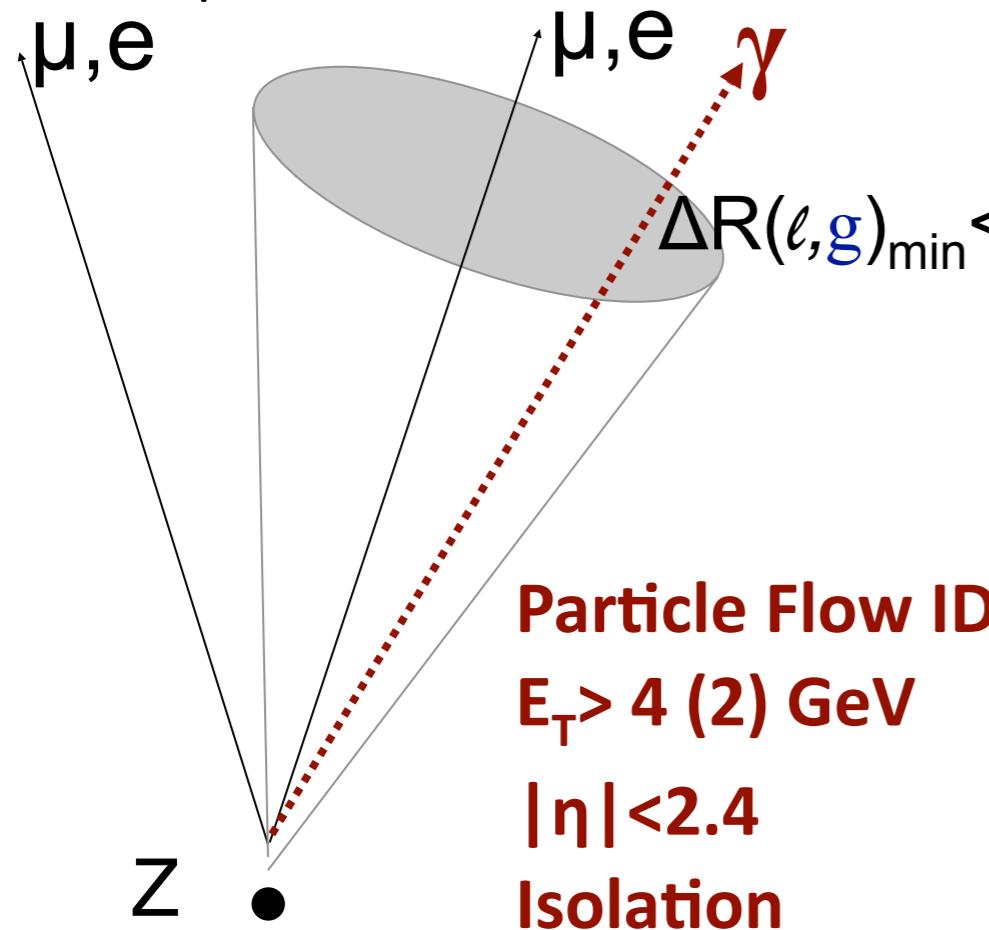
Muon reconstruction and identification

- Start with particle flow muons
- Efficiency above 96% down to $p_T = 5$ GeV
 - Above 99% efficiency for $p_T > 10$ GeV
 - Efficiency in data using J/Ψ and Z peak



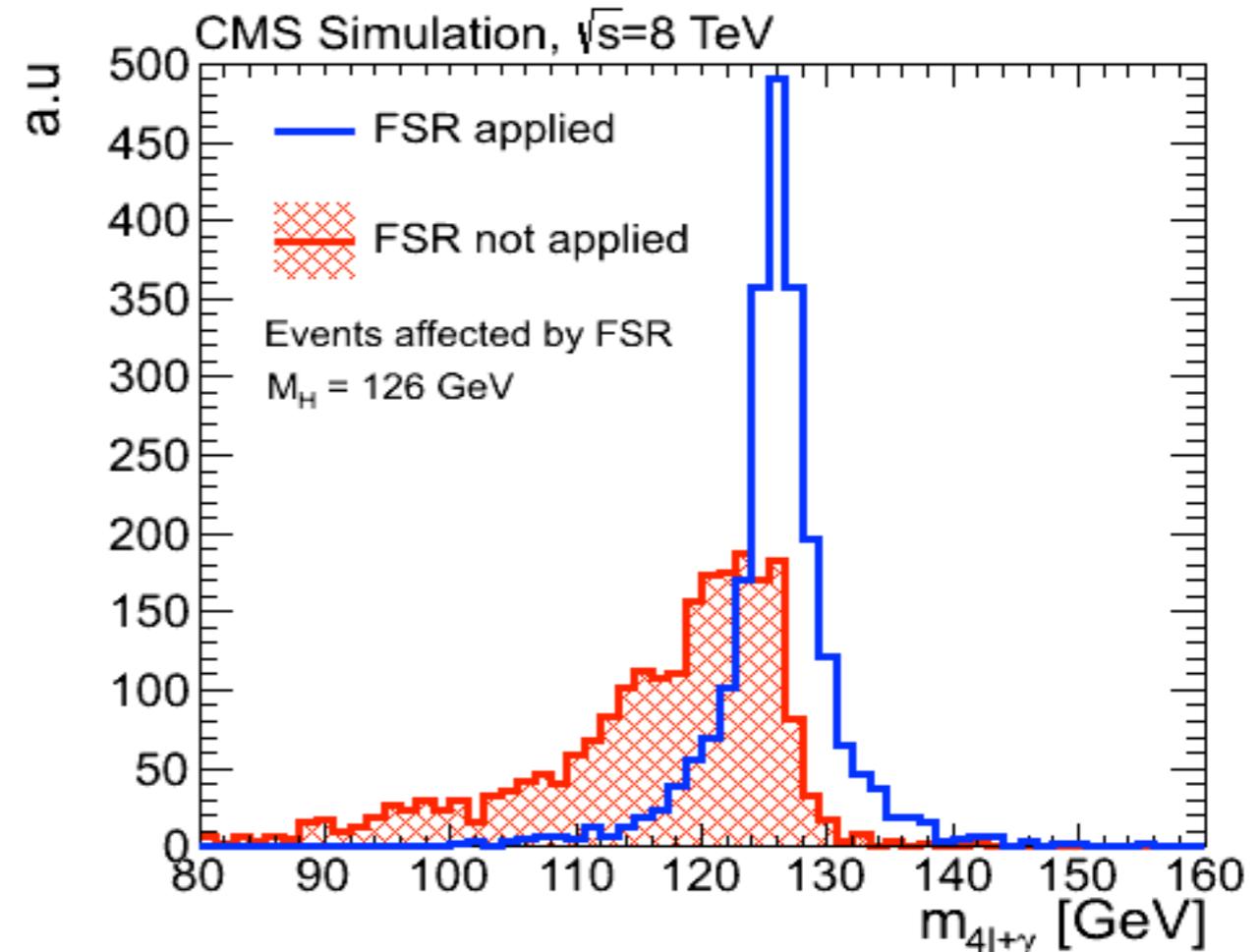
Final State Radiation recovery Z->ll

- Applied on each Z for photons near the leptons



- Associates photon with Z if:
 - $M(l\bar{l} + \gamma) < 100 \text{ GeV}$
 - $|M(l\bar{l} + \gamma) - M_Z| < |M(l\bar{l}) - M_Z|$

- Expected Performance for $M_H = 126 \text{ GeV}$
 - 6% of events affected
 - Average purity of 80%
 - 2% added in analysis

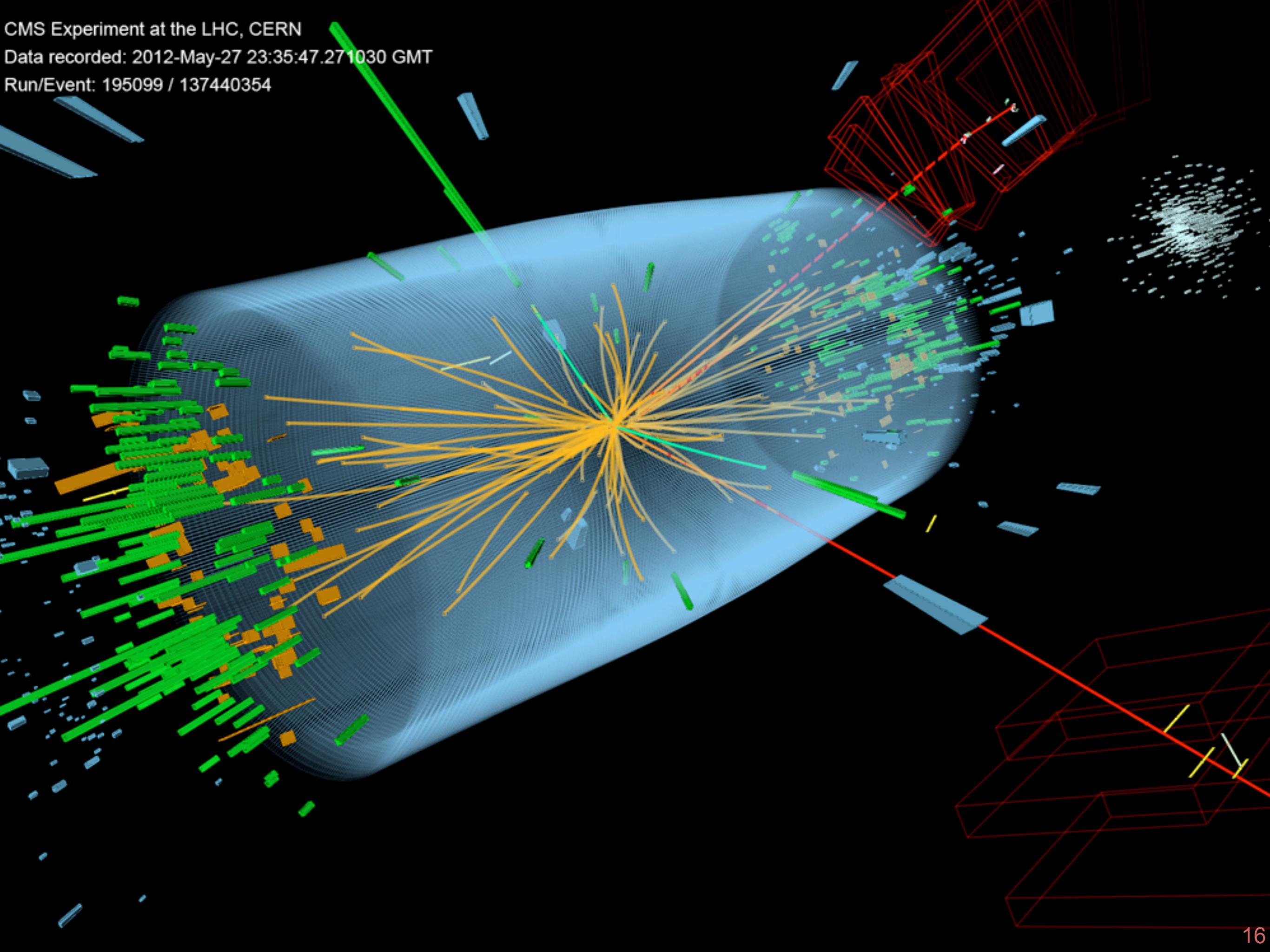


$$H\rightarrow Z^{(*)}Z^{(*)}$$

CMS Experiment at the LHC, CERN

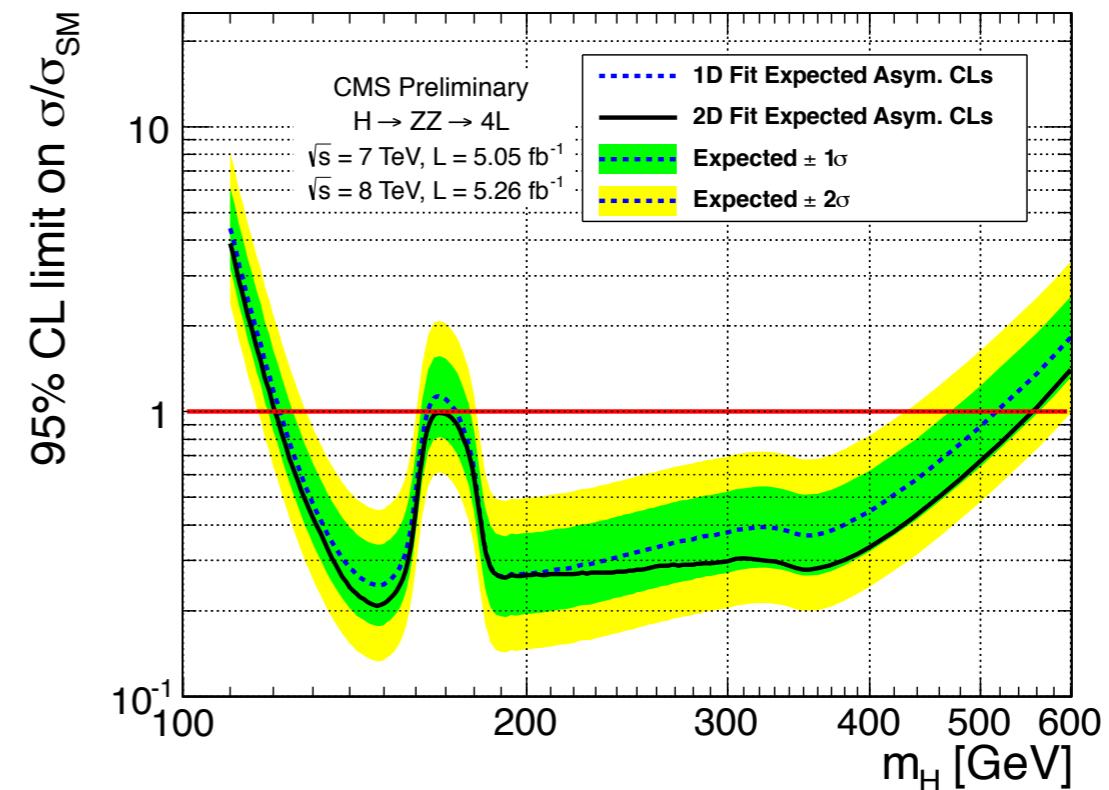
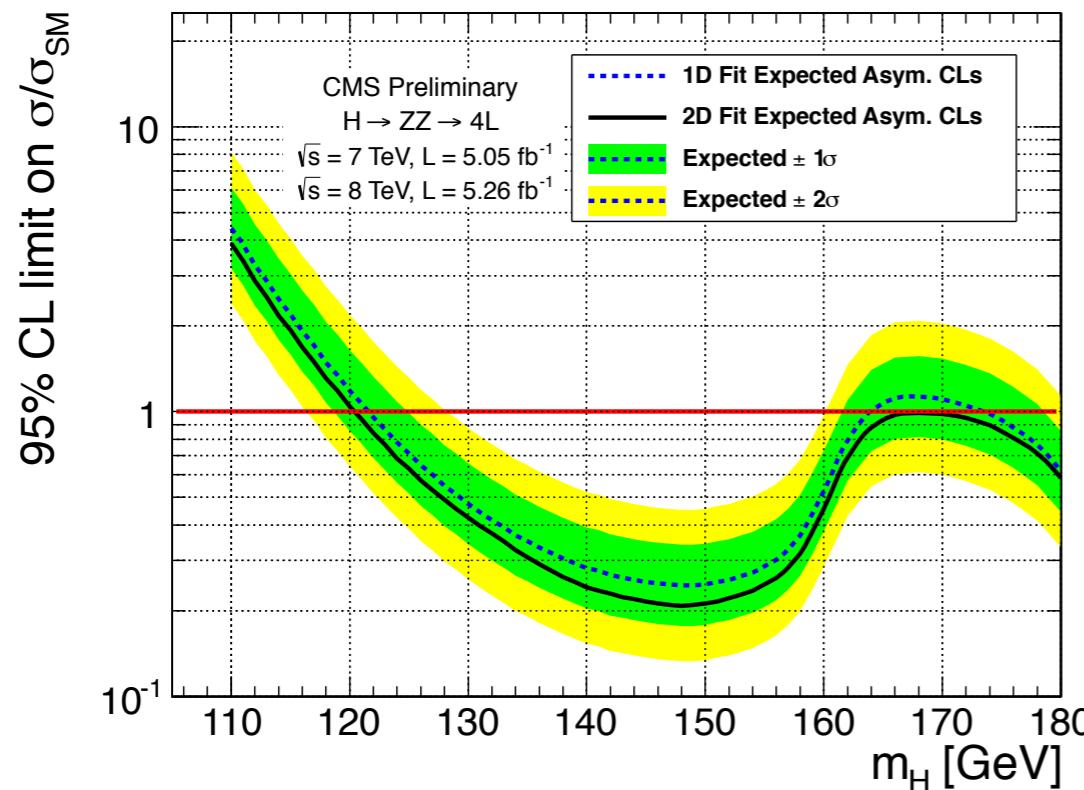
Data recorded: 2012-May-27 23:35:47.271030 GMT

Run/Event: 195099 / 137440354

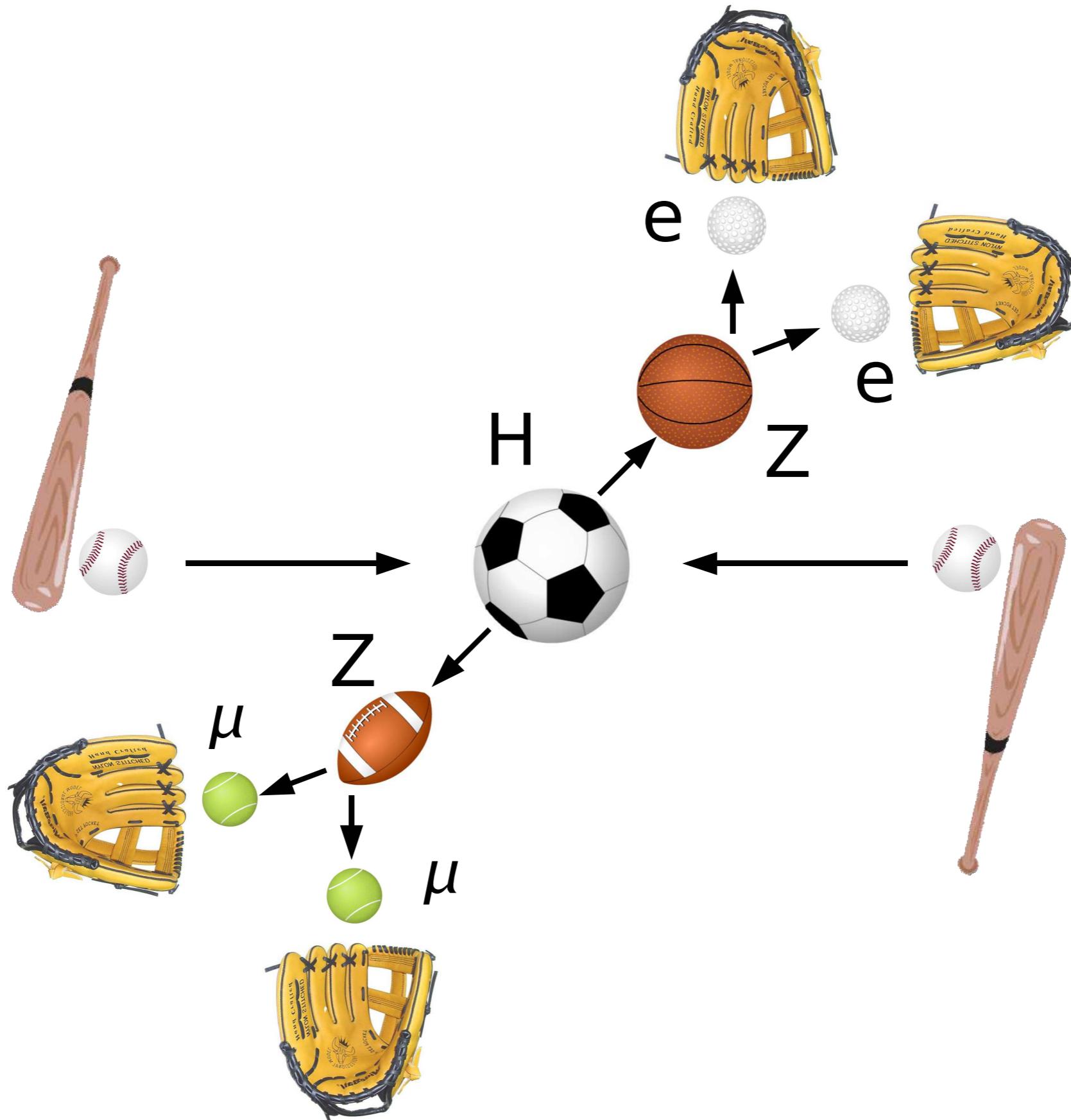


$$H \rightarrow Z^{(*)} Z^{(*)} \rightarrow 4\ell$$

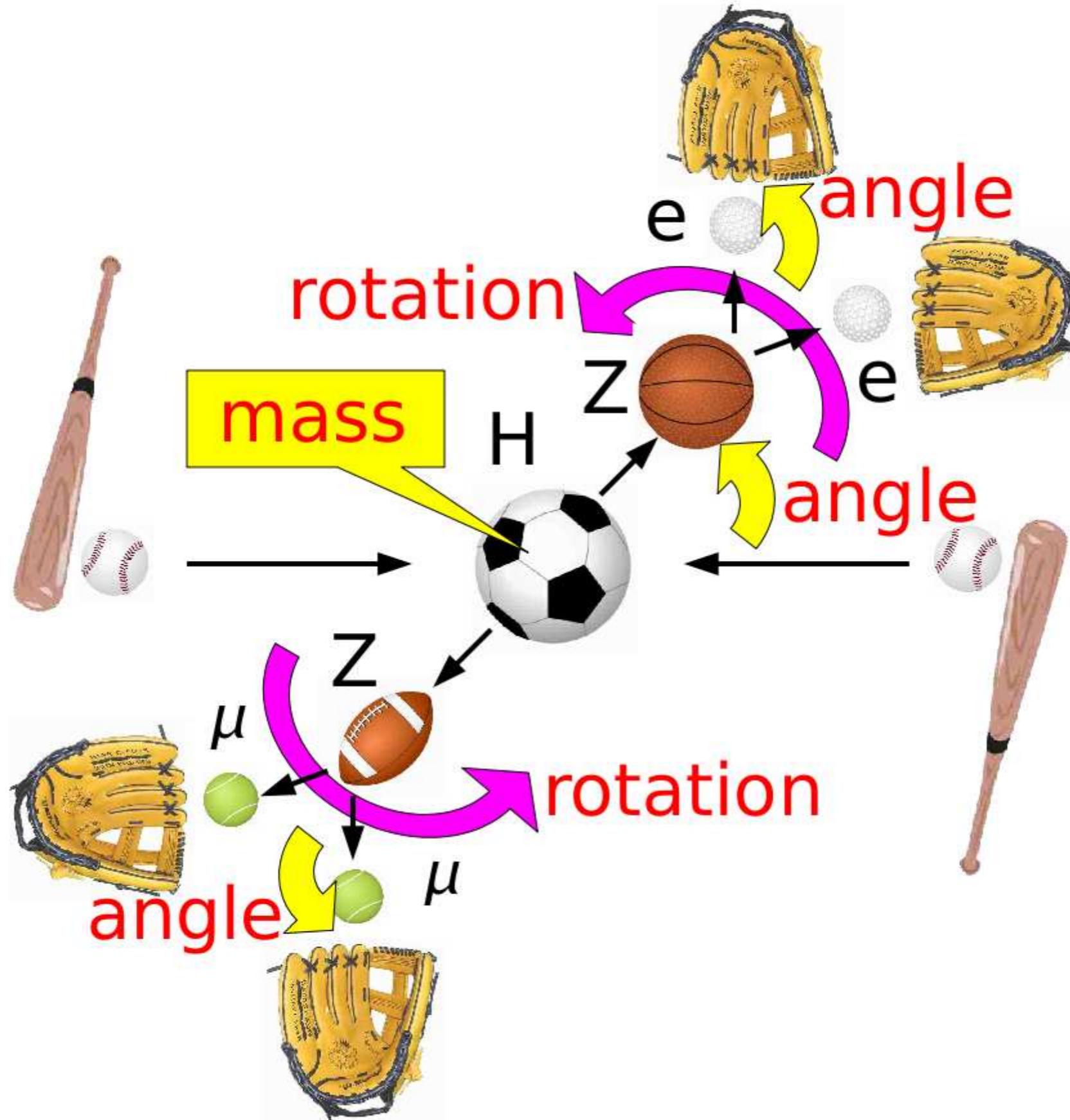
- Significant **improvements** since 2011, apply to both **7** and **8 TeV** data
 - electron identification and isolation
 - muon identification and isolation
 - FSR recovery
 - full **kinematics** (MELA)
 - 2D statistical analysis ($m_{4\ell}$ + kinematics)
- expected signif. $\sim 2.7\sigma \rightarrow 3.8\sigma$



Kinematics in $H \rightarrow Z^{(*)} Z^{(*)}$



Kinematics in $H \rightarrow Z^{(*)}Z^{(*)}$



Matrix Element Likelihood Analysis (MELA)

$$\text{MELA} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})} \right]^{-1}$$

- Used in $H \rightarrow ZZ^{(*)} \rightarrow 2q2\ell$ in 2011

JHEP04(2012)036

from PRD81,075022(2010)

- Discriminate **signal** vs **background**

– QCD effects suppressed (no p_T , Y)
independent of production mechanism

CMS Preliminary 2012 $\sqrt{s}=7 \text{ TeV}, L=5.05 \text{ fb}^{-1}; \sqrt{s}=8 \text{ TeV}, L=5.26 \text{ fb}^{-1}$

CMS Preliminary 2012 $\sqrt{s}=7 \text{ TeV}, L=5.05 \text{ fb}^{-1}; \sqrt{s}=8 \text{ TeV}, L=5.26 \text{ fb}^{-1}$

CMS Preliminary 2012 $\sqrt{s}=7 \text{ TeV}, L=5.05 \text{ fb}^{-1}; \sqrt{s}=8 \text{ TeV}, L=5.26 \text{ fb}^{-1}$

Andrei Gritsan, JHU

9 July 2012

MELA Probability Distributions

- $\mathcal{P}_{\text{bkg}} \propto$ POWHEG template ($m_{4\ell} < 180$ GeV): dominant $q\bar{q} \rightarrow Z\gamma^*$
 \propto JHEP11(2011)027 ($m_{4\ell} > 180$ GeV): dominant $q\bar{q} \rightarrow ZZ$
- $\mathcal{P}_{\text{sig}} \propto$ PRD81,075022(2010)

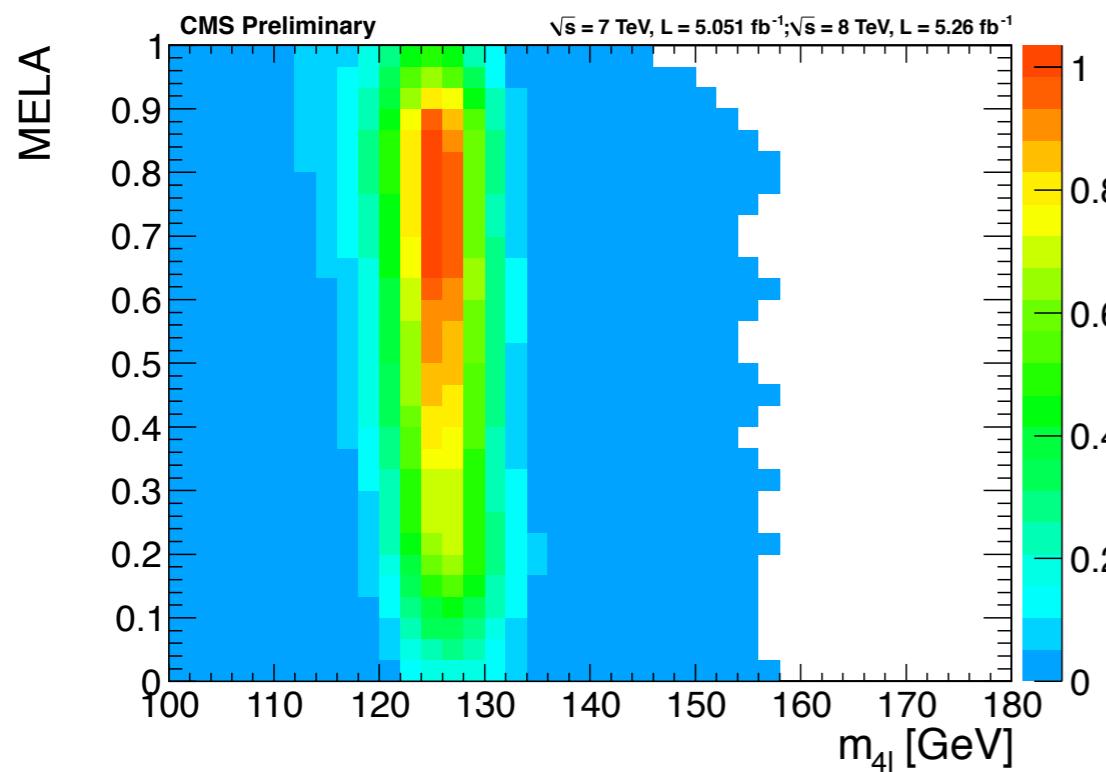
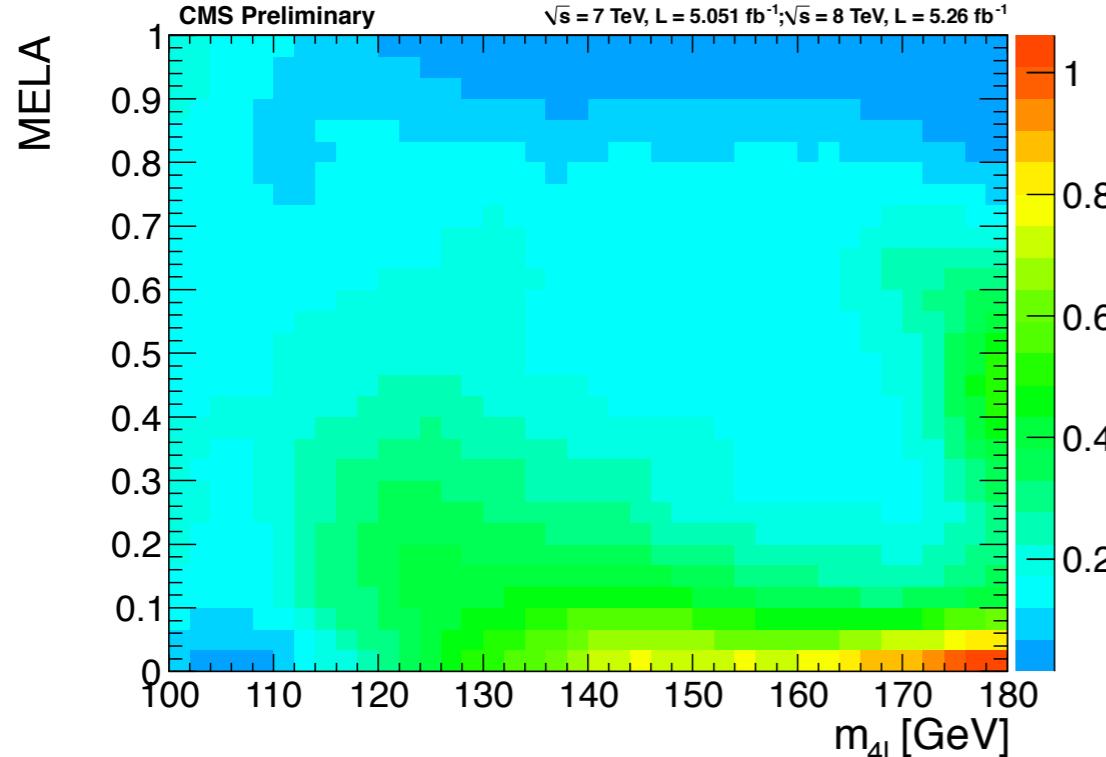
$$\begin{aligned}
F_{00}^J(\theta^*) \times & \left\{ 4 f_{00} \sin^2 \theta_1 \sin^2 \theta_2 + (f_{++} + f_{--}) ((1 + \cos^2 \theta_1)(1 + \cos^2 \theta_2) + 4R_1 R_2 \cos \theta_1 \cos \theta_2) \right. \\
& - 2(f_{++} - f_{--})(R_1 \cos \theta_1 (1 + \cos^2 \theta_2) + R_2 (1 + \cos^2 \theta_1) \cos \theta_2) \\
& + 4\sqrt{f_{++} f_{00}} (R_1 - \cos \theta_1) \sin \theta_1 (R_2 - \cos \theta_2) \sin \theta_2 \cos(\Phi + \phi_{++}) \\
& + 4\sqrt{f_{--} f_{00}} (R_1 + \cos \theta_1) \sin \theta_1 (R_2 + \cos \theta_2) \sin \theta_2 \cos(\Phi - \phi_{--}) \\
& \left. + 2\sqrt{f_{++} f_{--}} \sin^2 \theta_1 \sin^2 \theta_2 \cos(2\Phi + \phi_{++} - \phi_{--}) \right\} \quad \text{spin} = 0 \ \& \geq 2
\end{aligned}$$

$$\begin{aligned}
+ 4F_{11}^J(\theta^*) \times & \left\{ (f_{+0} + f_{0-})(1 - \cos^2 \theta_1 \cos^2 \theta_2) - (f_{+0} - f_{0-})(R_1 \cos \theta_1 \sin^2 \theta_2 + R_2 \sin^2 \theta_1 \cos \theta_2) \right. \\
& \left. + 2\sqrt{f_{+0} f_{0-}} \sin \theta_1 \sin \theta_2 (R_1 R_2 - \cos \theta_1 \cos \theta_2) \cos(\Phi + \phi_{+0} - \phi_{0-}) \right\}
\end{aligned}$$

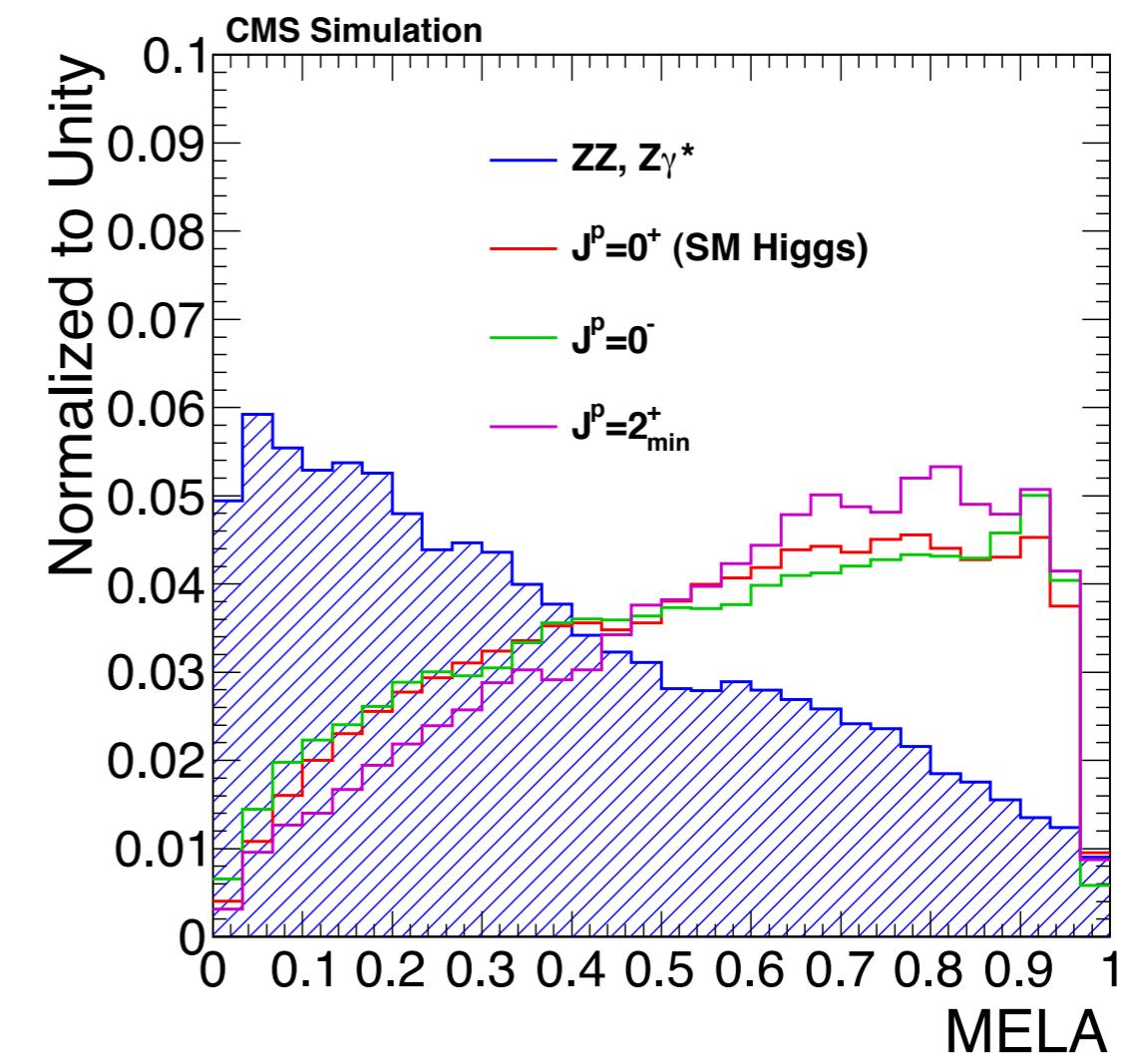
$$\begin{aligned}
+ 4F_{-11}^J(\theta^*) \times & (-1)^J \times \left\{ (f_{+0} + f_{0-})(R_1 R_2 + \cos \theta_1 \cos \theta_2) - (f_{+0} - f_{0-})(R_1 \cos \theta_2 + R_2 \cos \theta_1) \right. \\
& \left. + 2\sqrt{f_{+0} f_{0-}} \sin \theta_1 \sin \theta_2 \cos(\Phi + \phi_{+0} - \phi_{0-}) \right\} \sin \theta_1 \sin \theta_2 \cos(2\Psi) \quad \text{spin} = 1 \ \& \geq 2
\end{aligned}$$

$$\begin{aligned}
+ 2F_{22}^J(\theta^*) \times & f_{+-} \left\{ (1 + \cos^2 \theta_1)(1 + \cos^2 \theta_2) - 4R_1 R_2 \cos \theta_1 \cos \theta_2 \right\} \\
+ 2F_{-22}^J(\theta^*) \times & (-1)^J \times f_{+-} \sin^2 \theta_1 \sin^2 \theta_2 \cos(4\Psi) \quad \text{spin} \geq 2 \text{ unique} \quad + \dots \text{interference terms}
\end{aligned}$$

2D analysis MELA vs $m_{4\ell}$



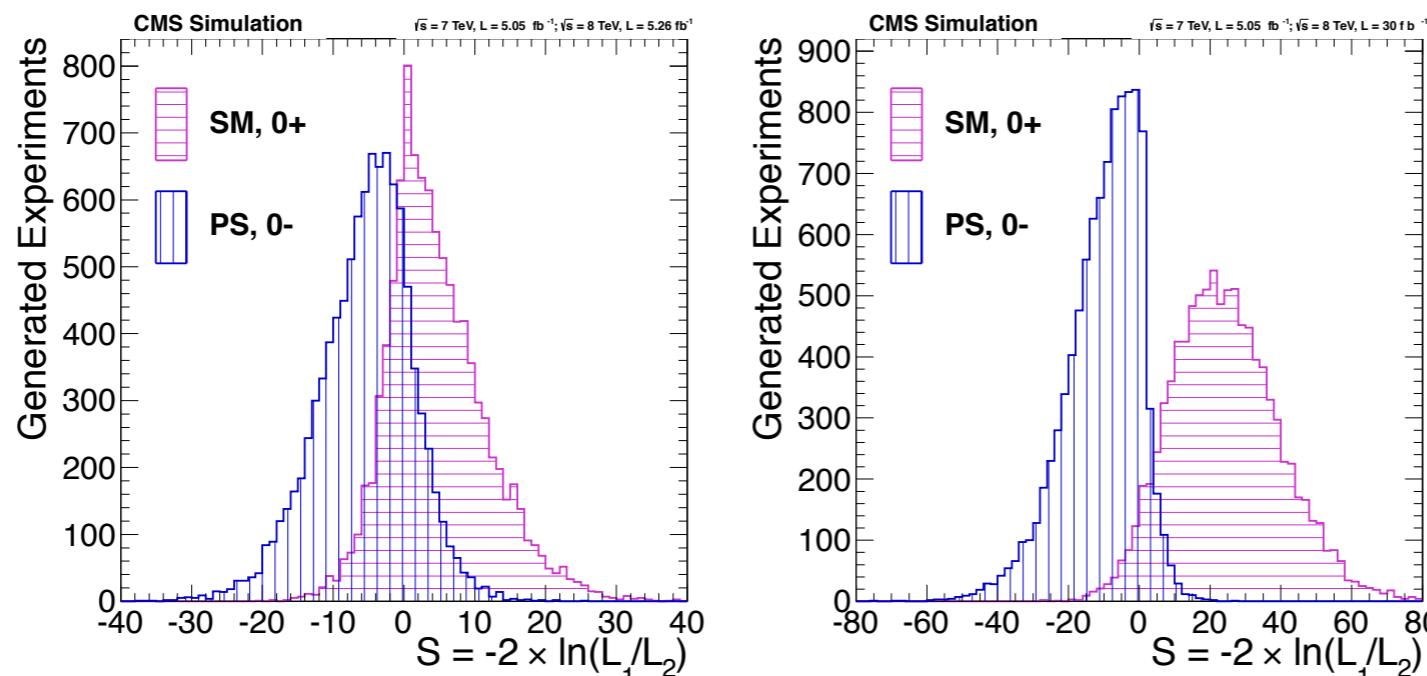
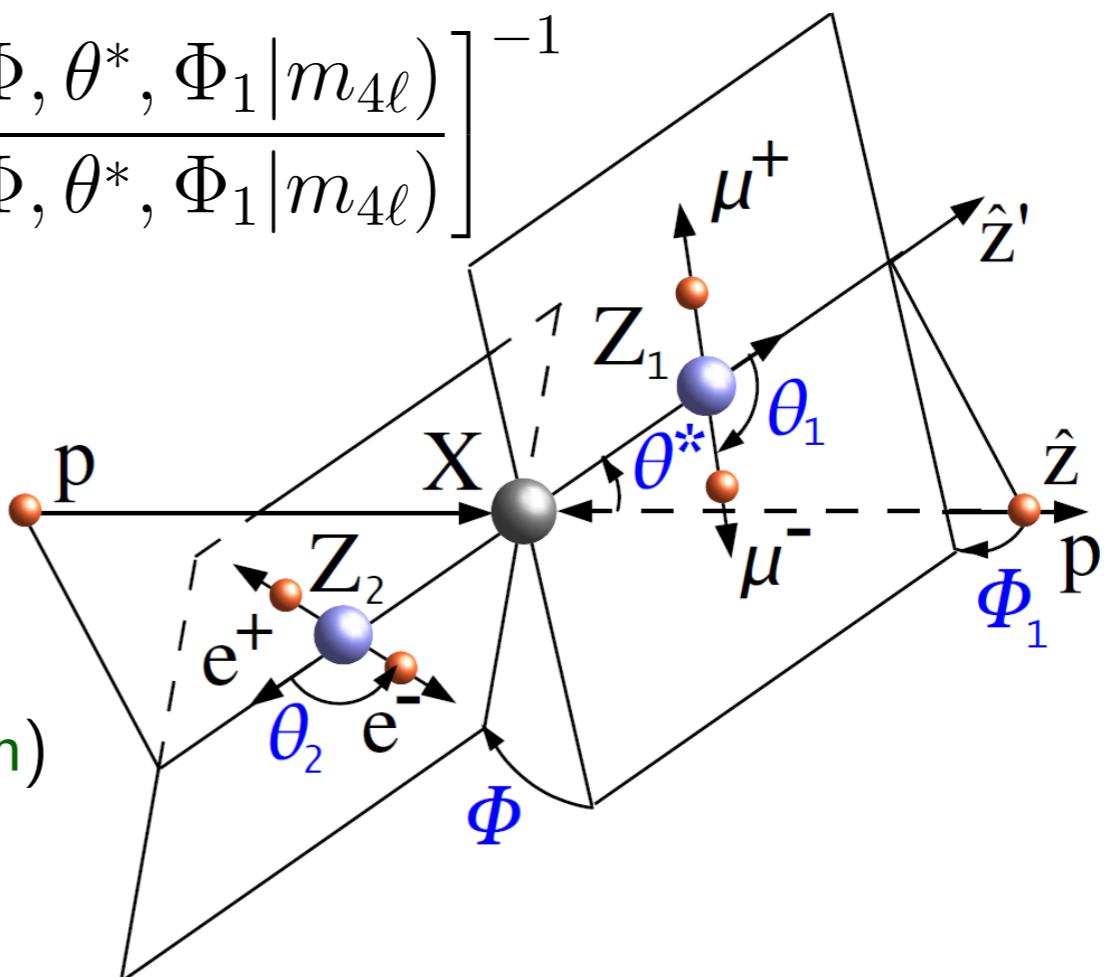
- Model with full simulation
 - include interference
 - powerful **sig.-bkg.** separation
 - little model-dependence



MELA for Spin / Parity

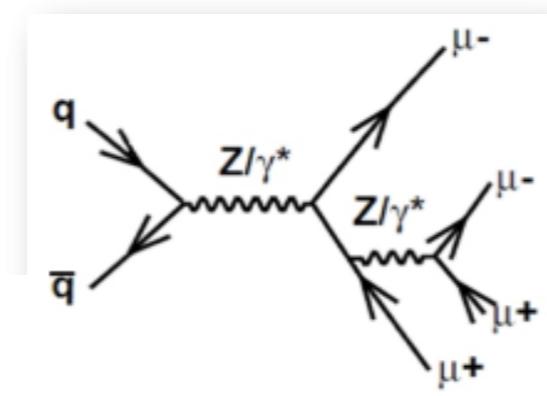
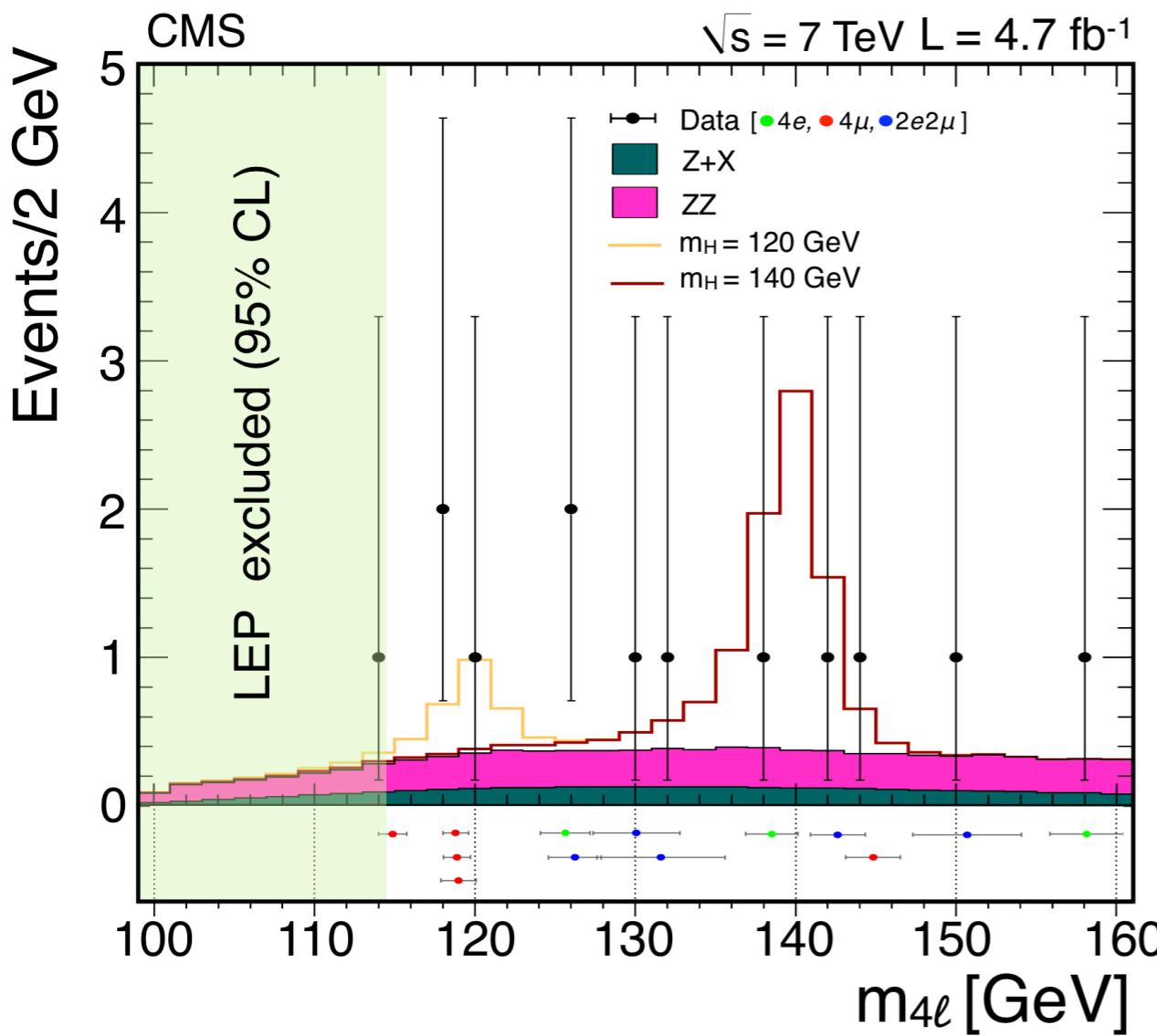
$$\text{psMELA} = \left[1 + \frac{\mathcal{P}_{0^-}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{0^+}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})} \right]^{-1}$$

- Hypothesis testing
 - scalar (0^+) vs pseudoscalar (0^-)
 - may include any other model
- Simulation (<http://www.pha.jhu.edu/spin>)
 - expected separation 1.6σ now
 - 3.1σ with $5+30 \text{ fb}^{-1}$

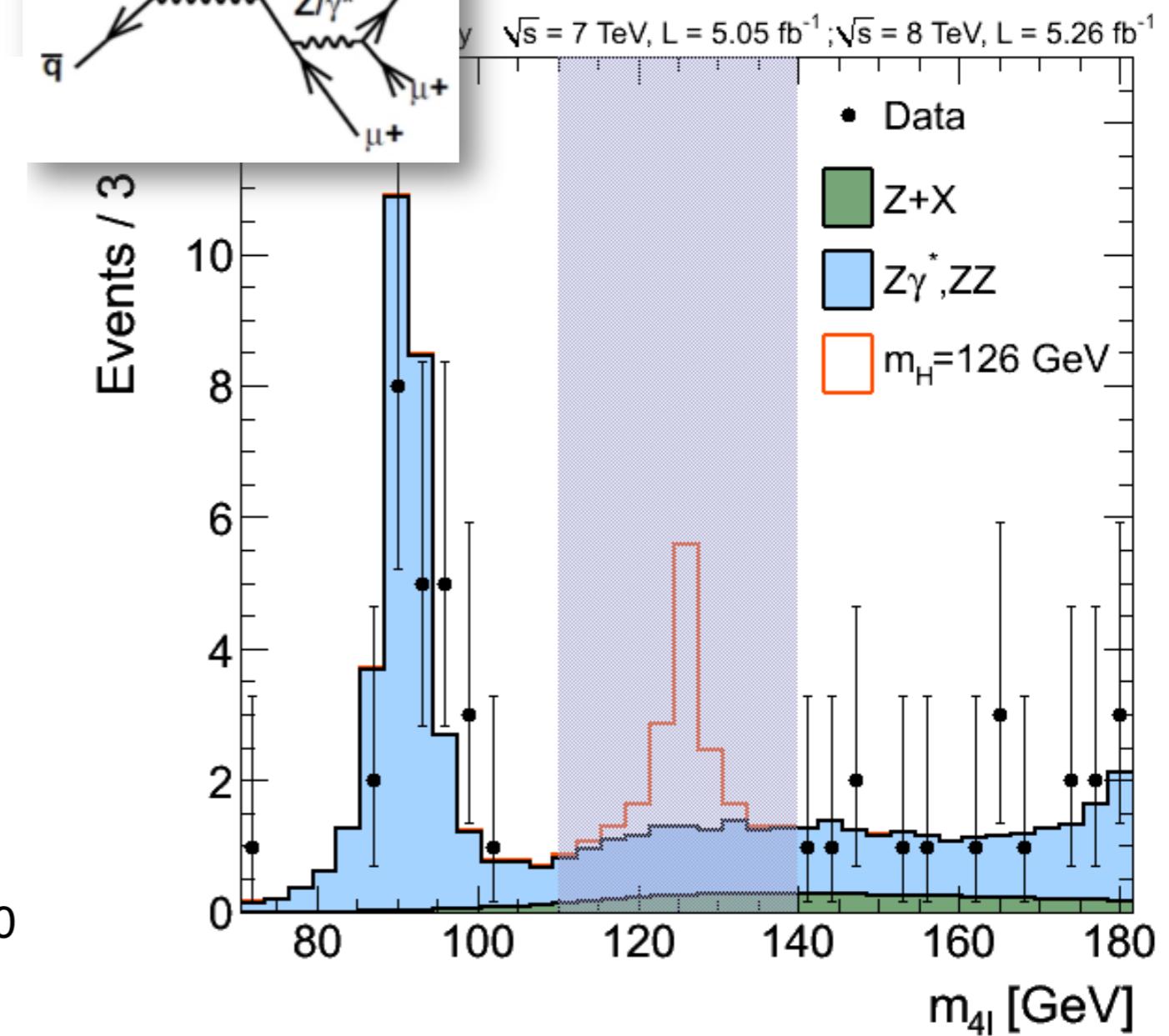


Analysis performed “blind”

Last year



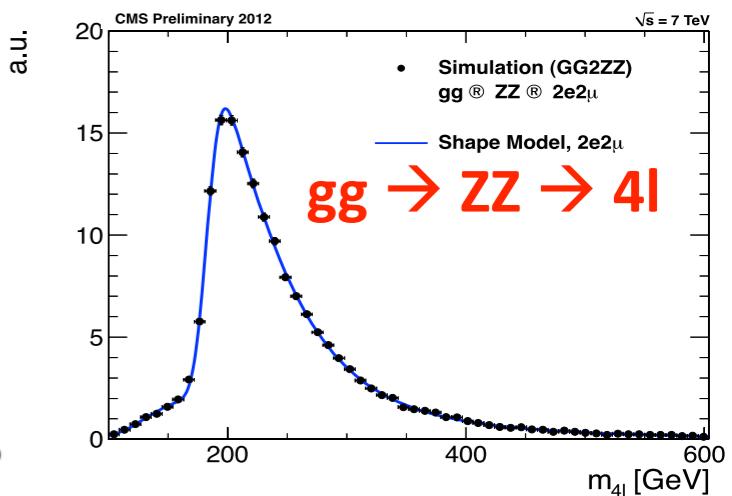
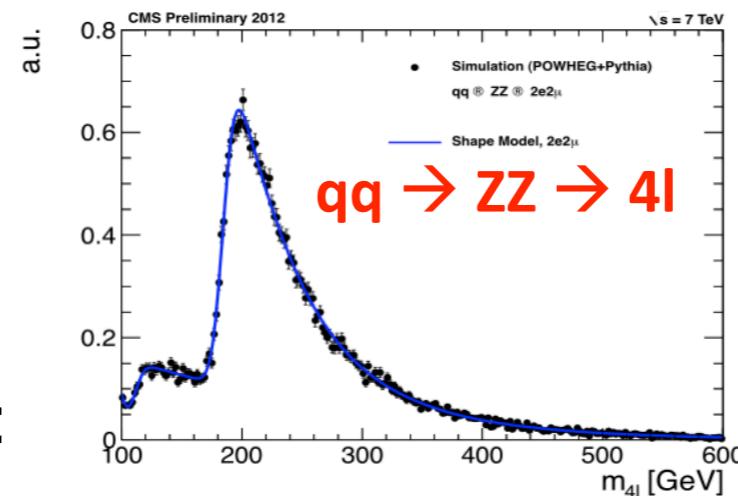
This year



Background models

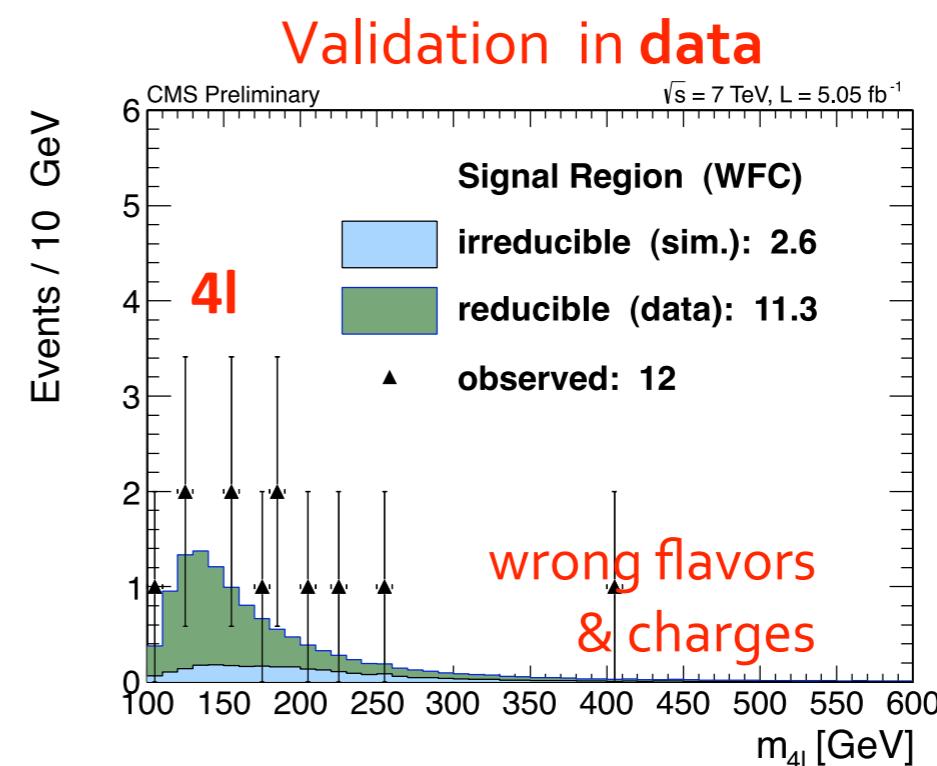
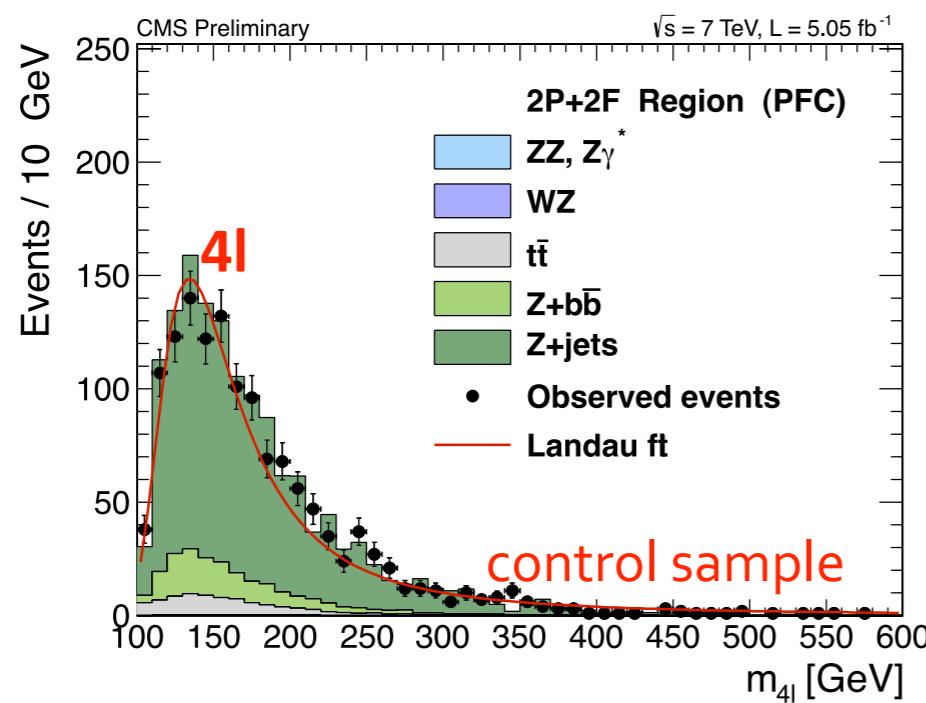
- **Irreducible background $ZZ \rightarrow 4l$**

- Estimated using simulation
- Phenomenological shape models
- Corrected for data/simulation scale

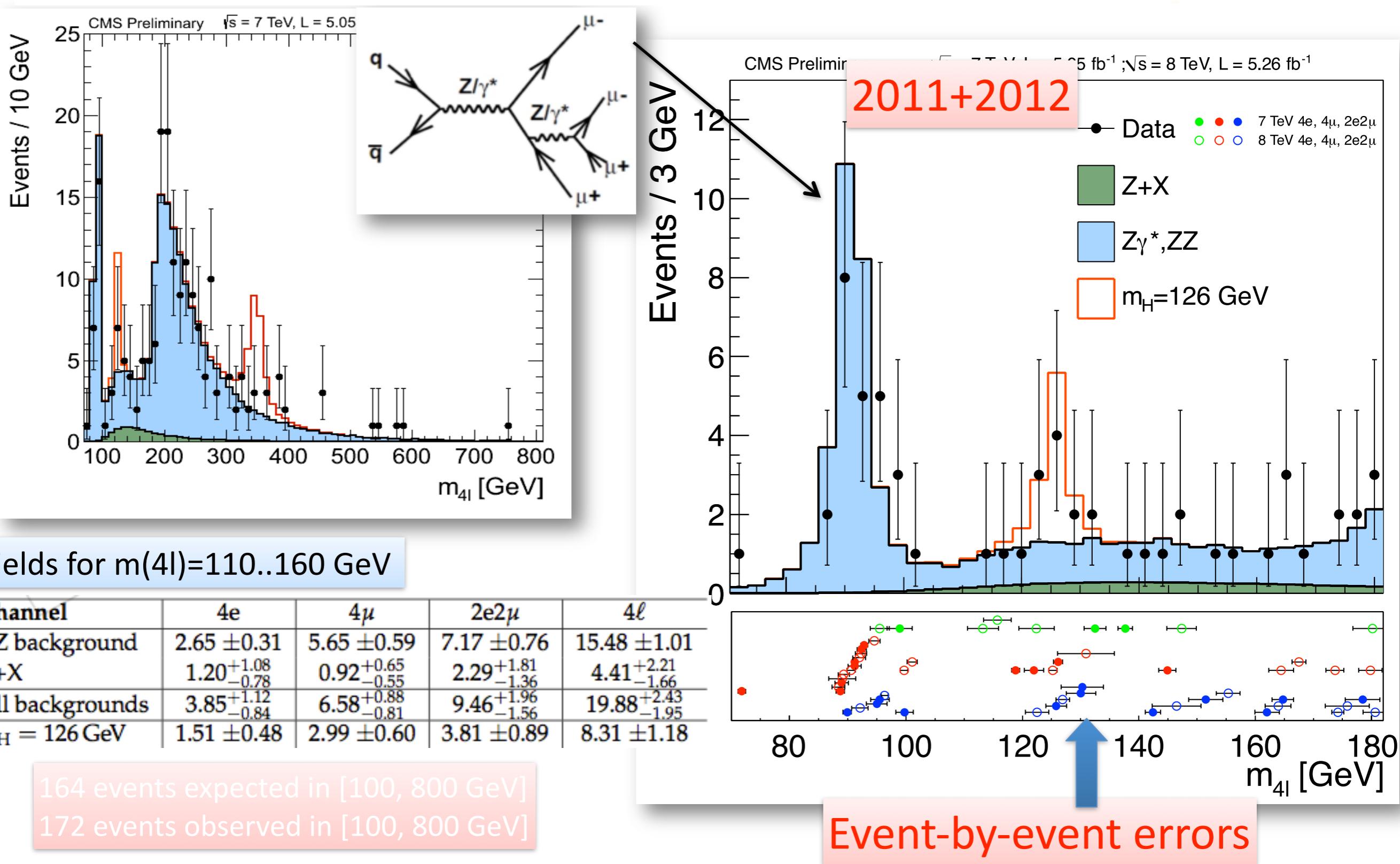


- **Reducible backgrounds estimated**

- Extrapolation from control samples enriched with misidentified leptons
- Total uncertainty ~50%



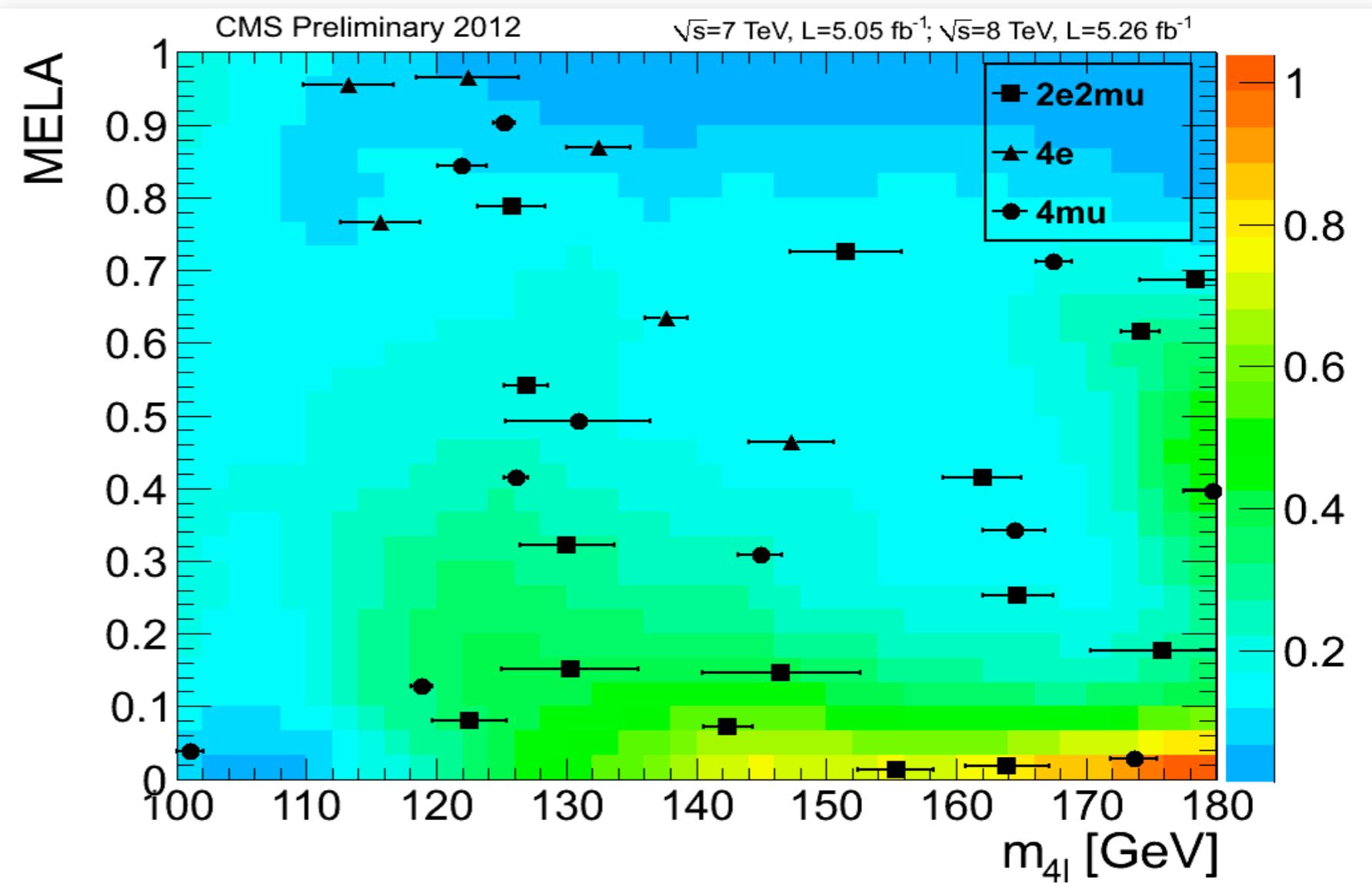
Results: $m(4l)$ spectrum



Results: MELA 2D plots

Perform 2D fit

- MELA discriminant versus m_{4l}
- Data points shown with per-event mass uncertainties

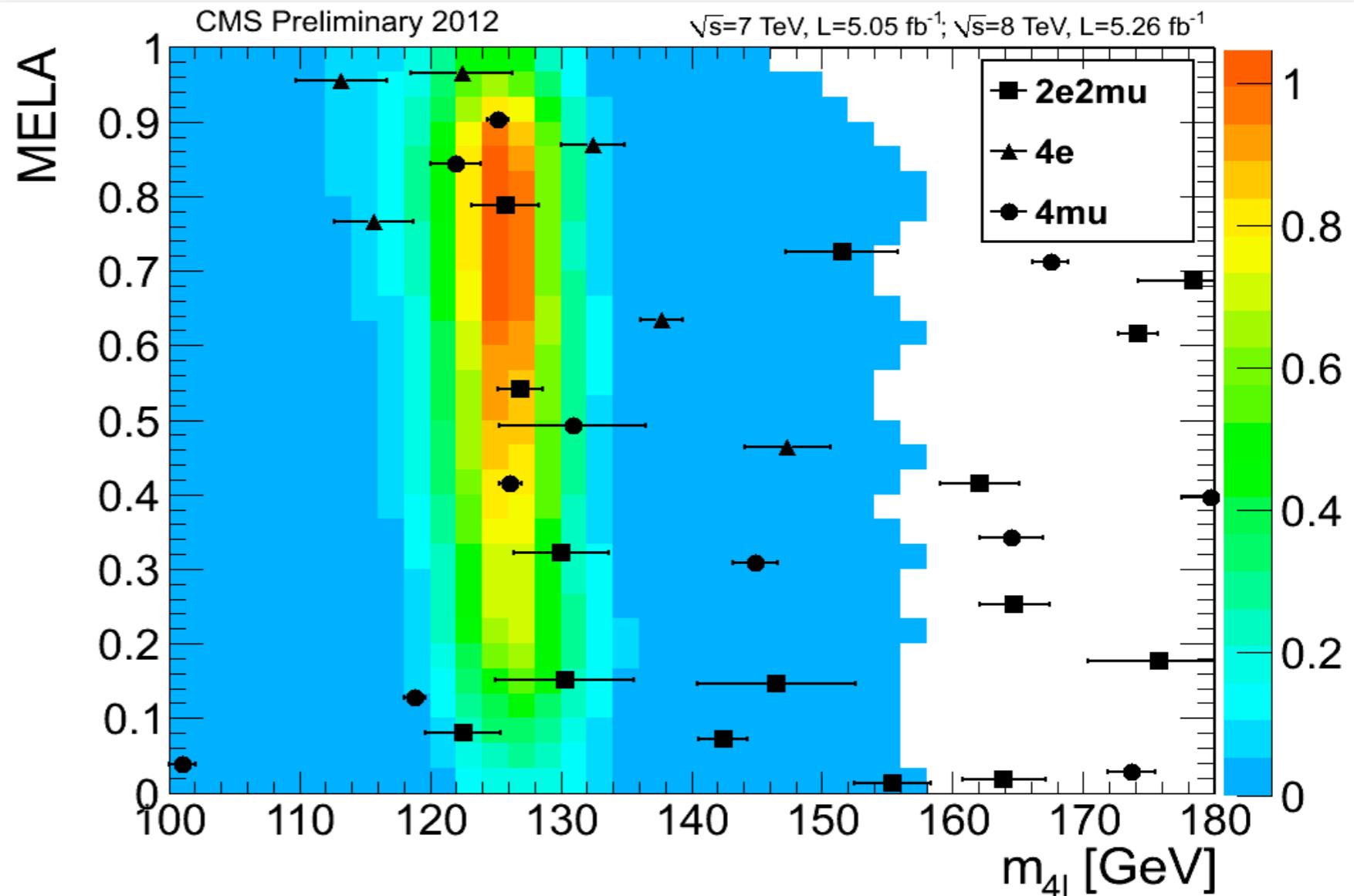


Data w.r.t. background expectation

Results: MELA 2D plots

Perform 2D fit

- MELA discriminant versus m_{4l}
- Data points shown with per-event mass uncertainties

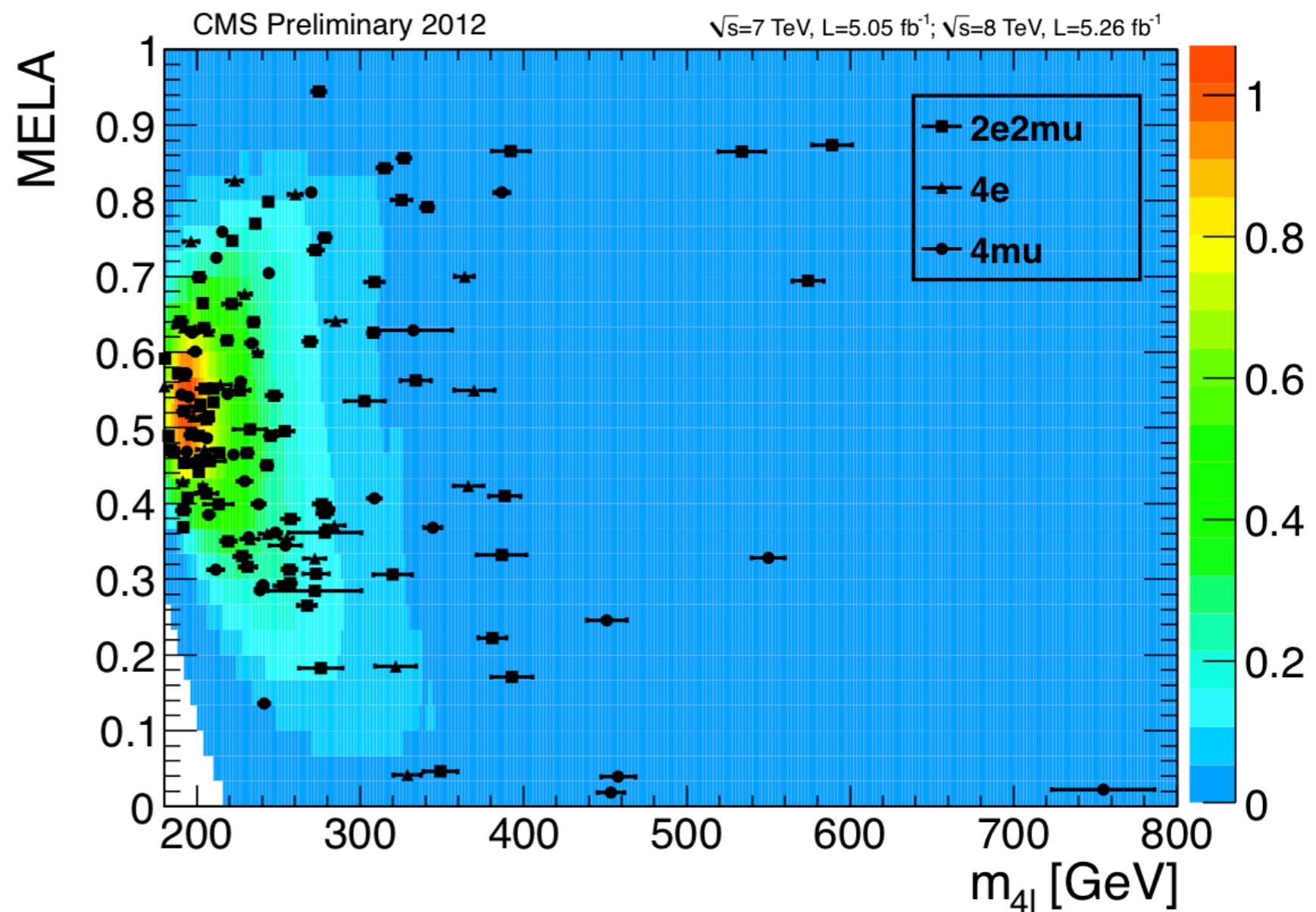


Data w.r.t 126 GeV Higgs Expectation

Results: MELA 2D plots: high mass

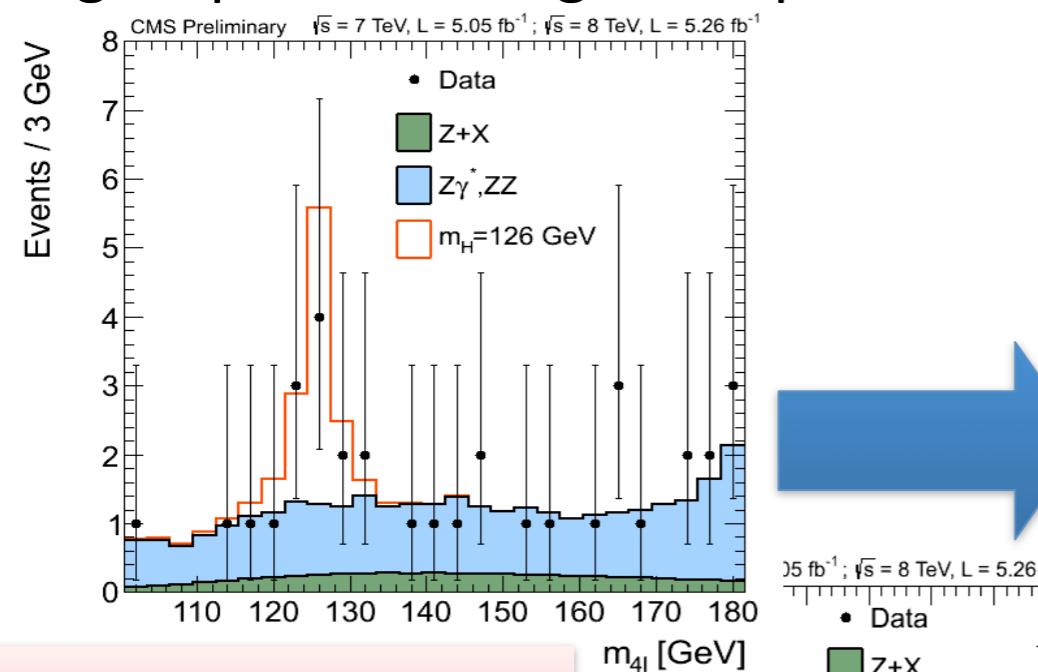
Perform 2D fit

- MELA discriminant versus m_{4l}
- Data points shown with per-event mass uncertainties

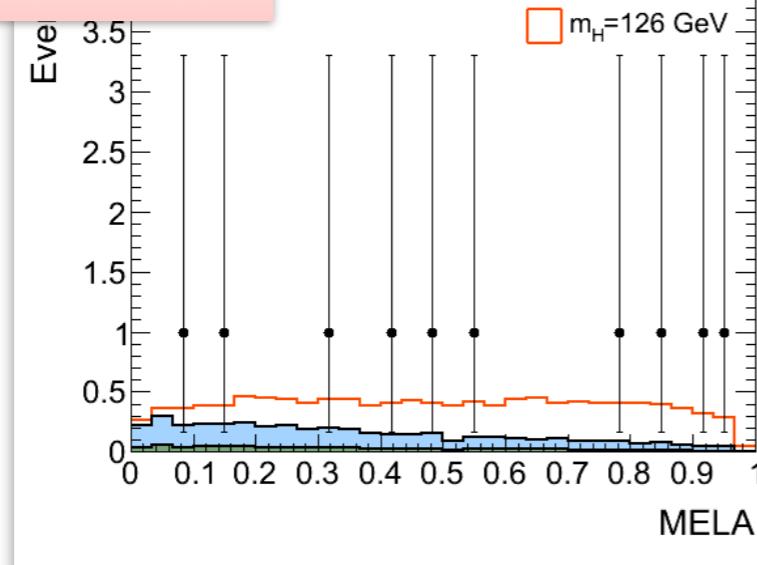


Low mass region with MELA cut

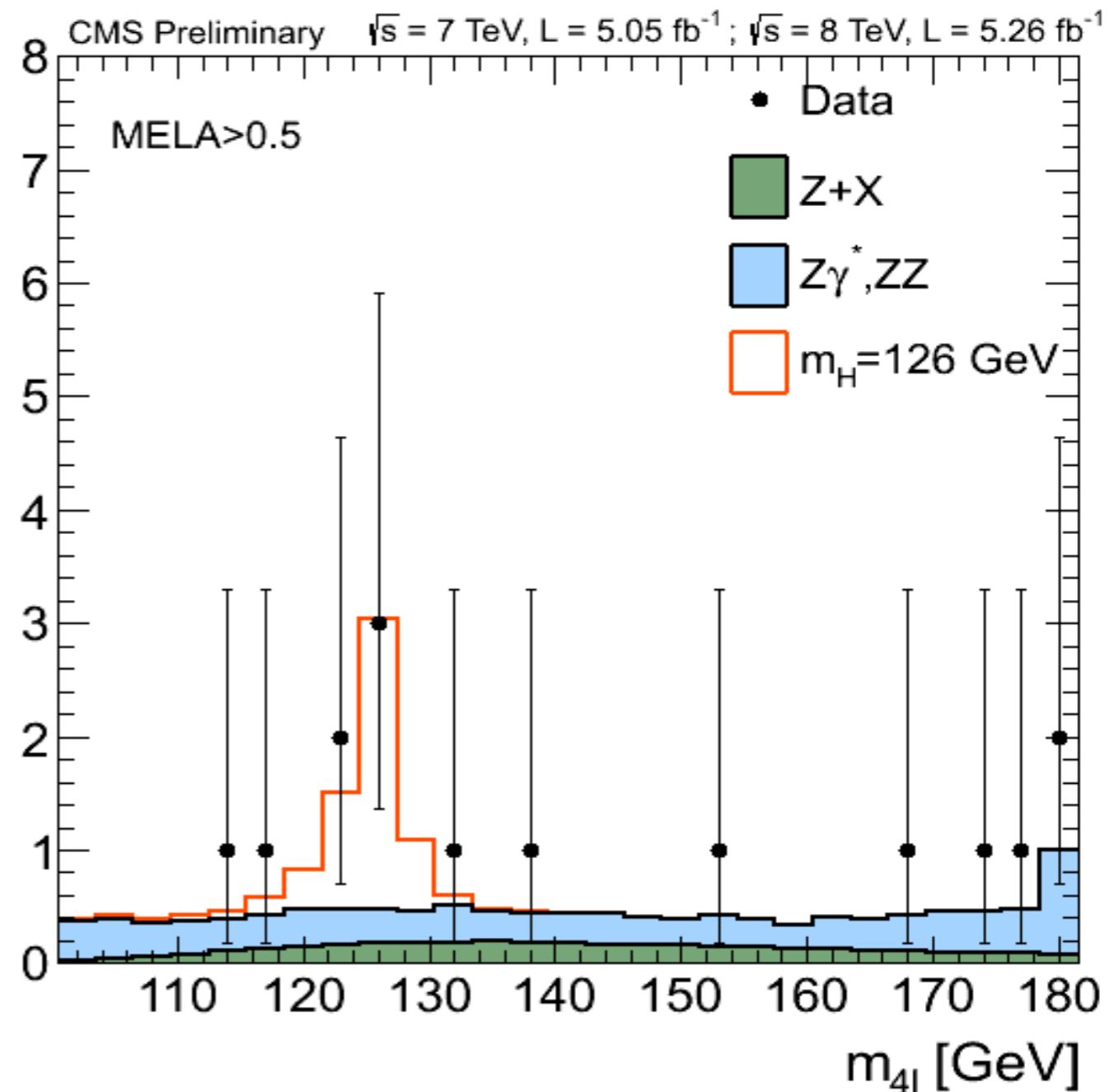
- Enrich the signal MELA > 0.5
- Cut value chosen such that
- signal prob. > background prob.



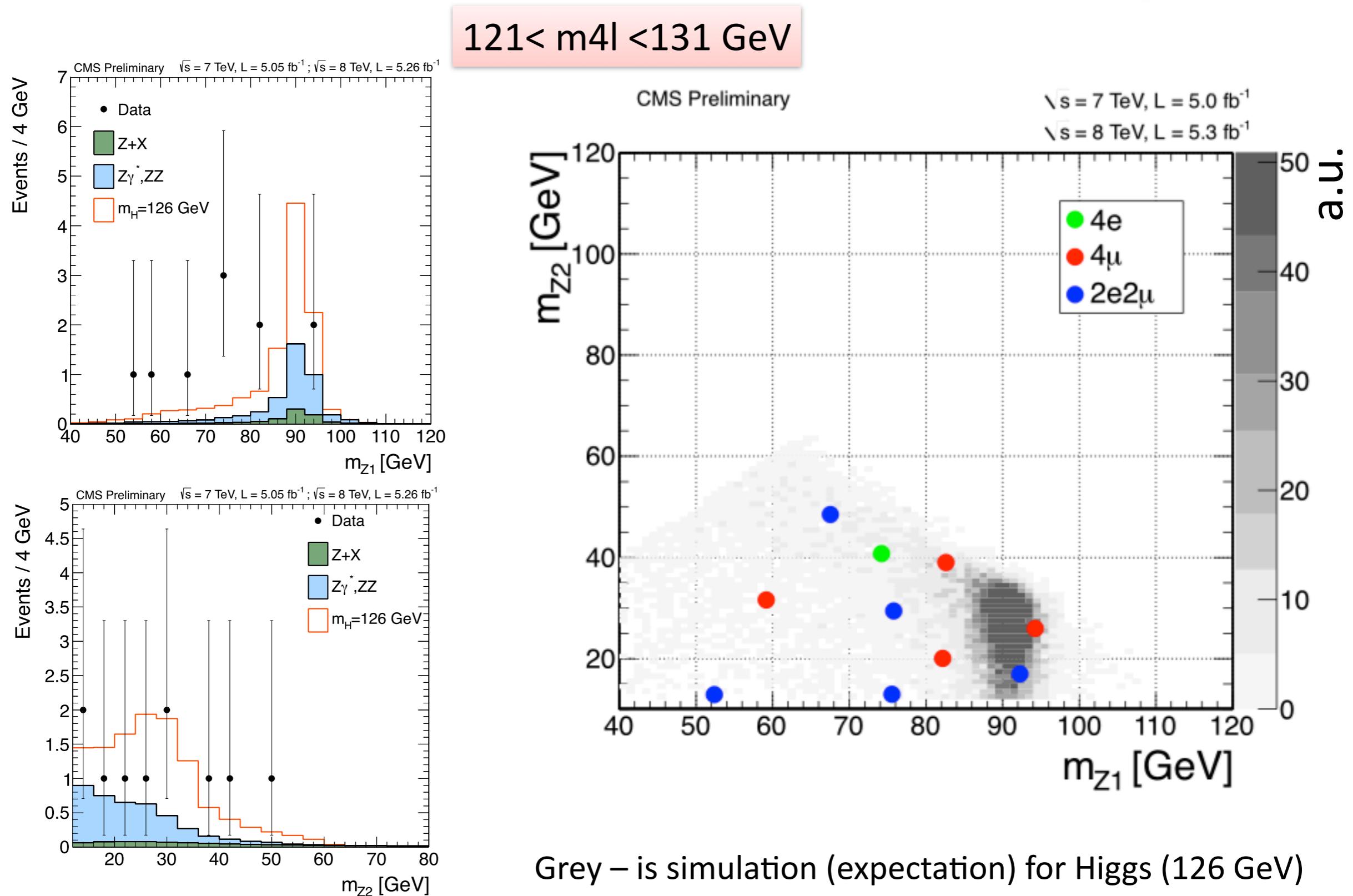
$121 < m_{4l} < 131 \text{ GeV}$



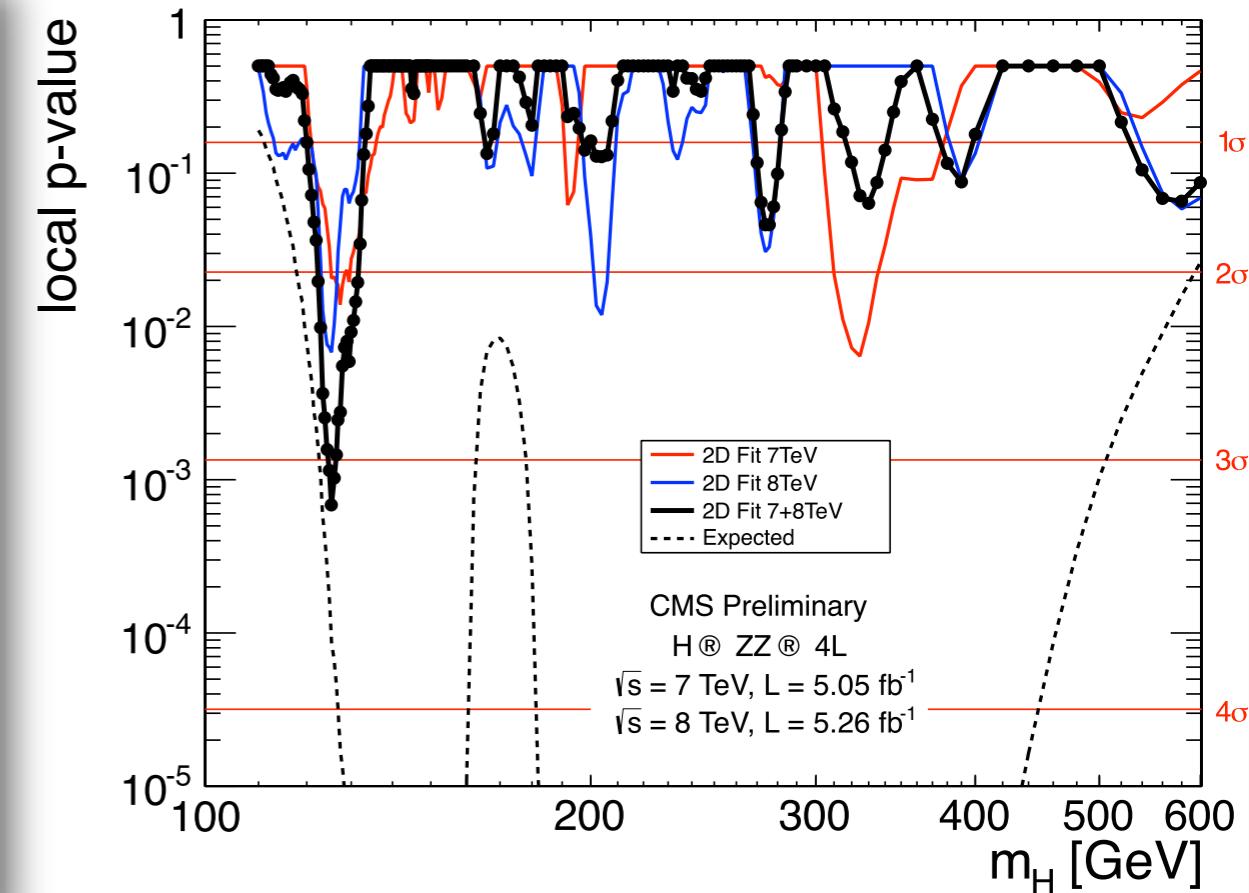
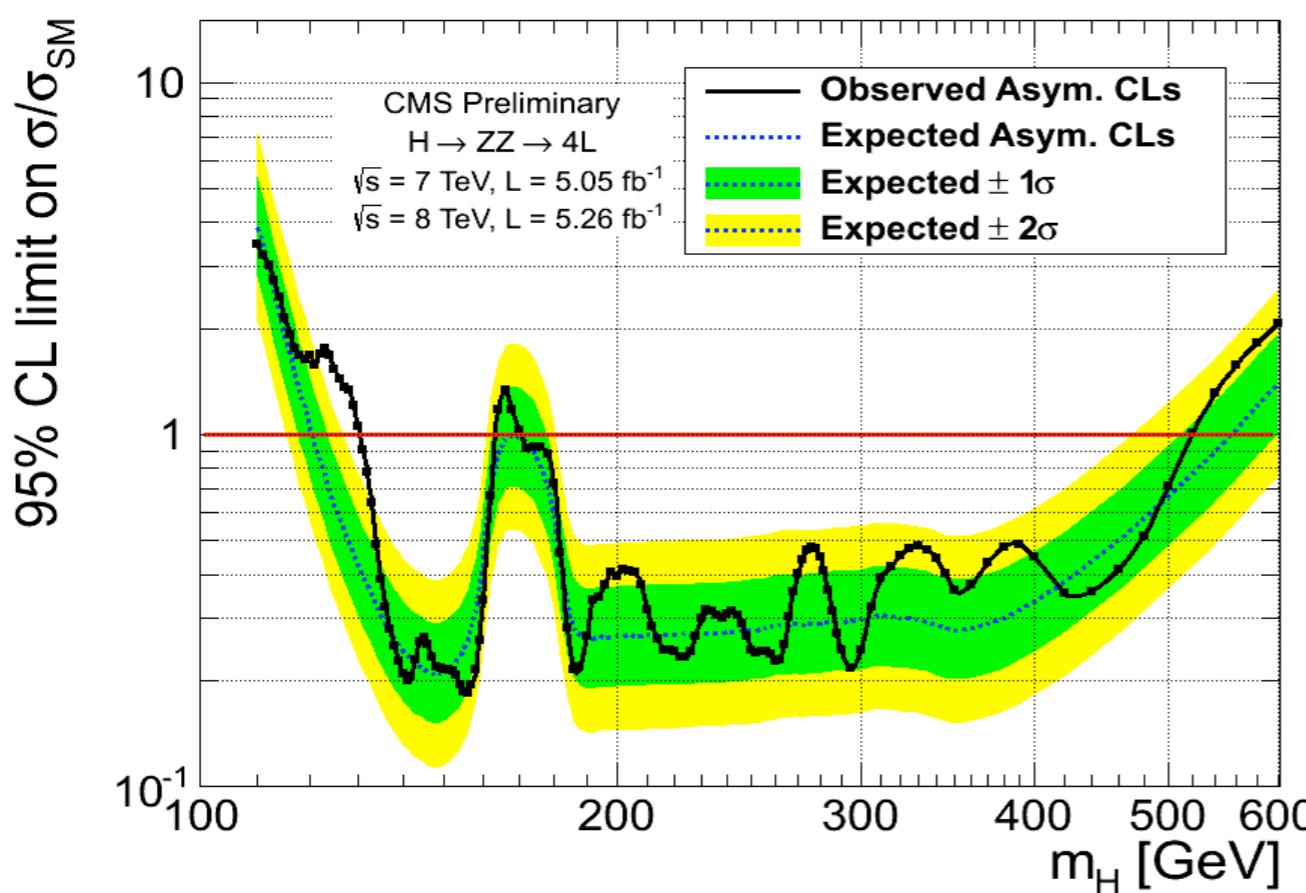
Events / 3 GeV



Two-lepton invariant mass plots



Limits and p-values



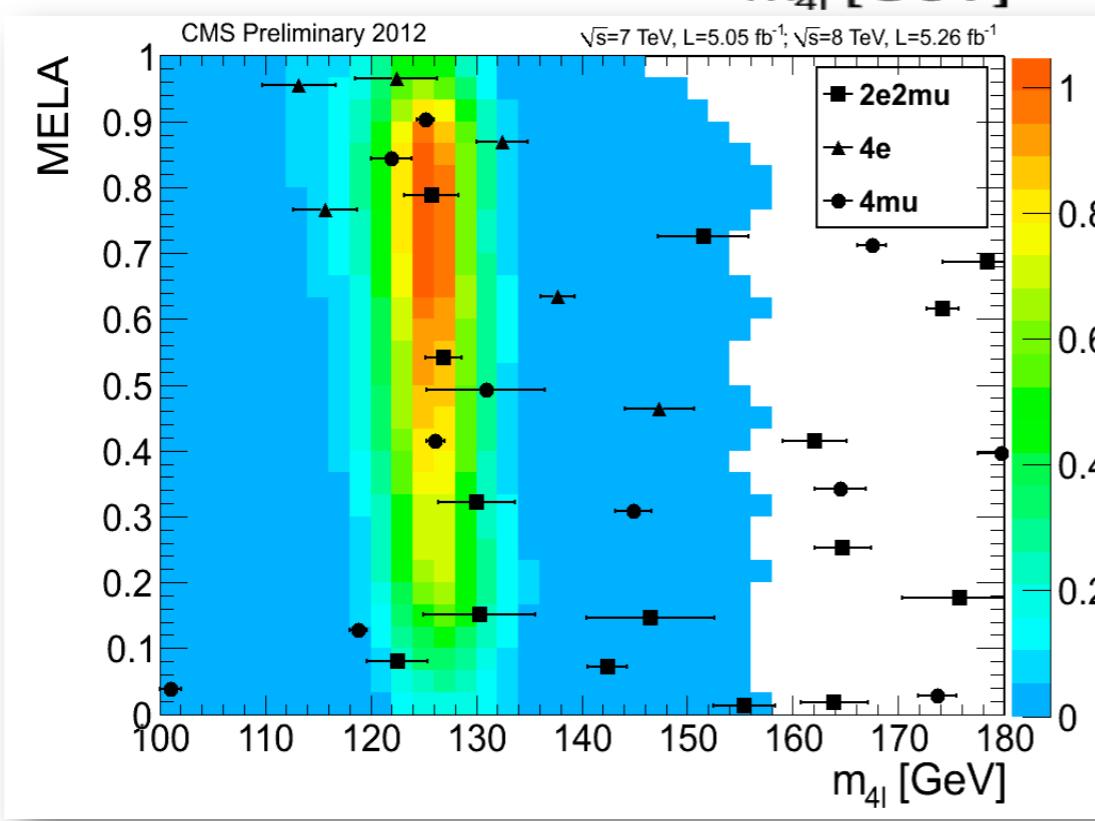
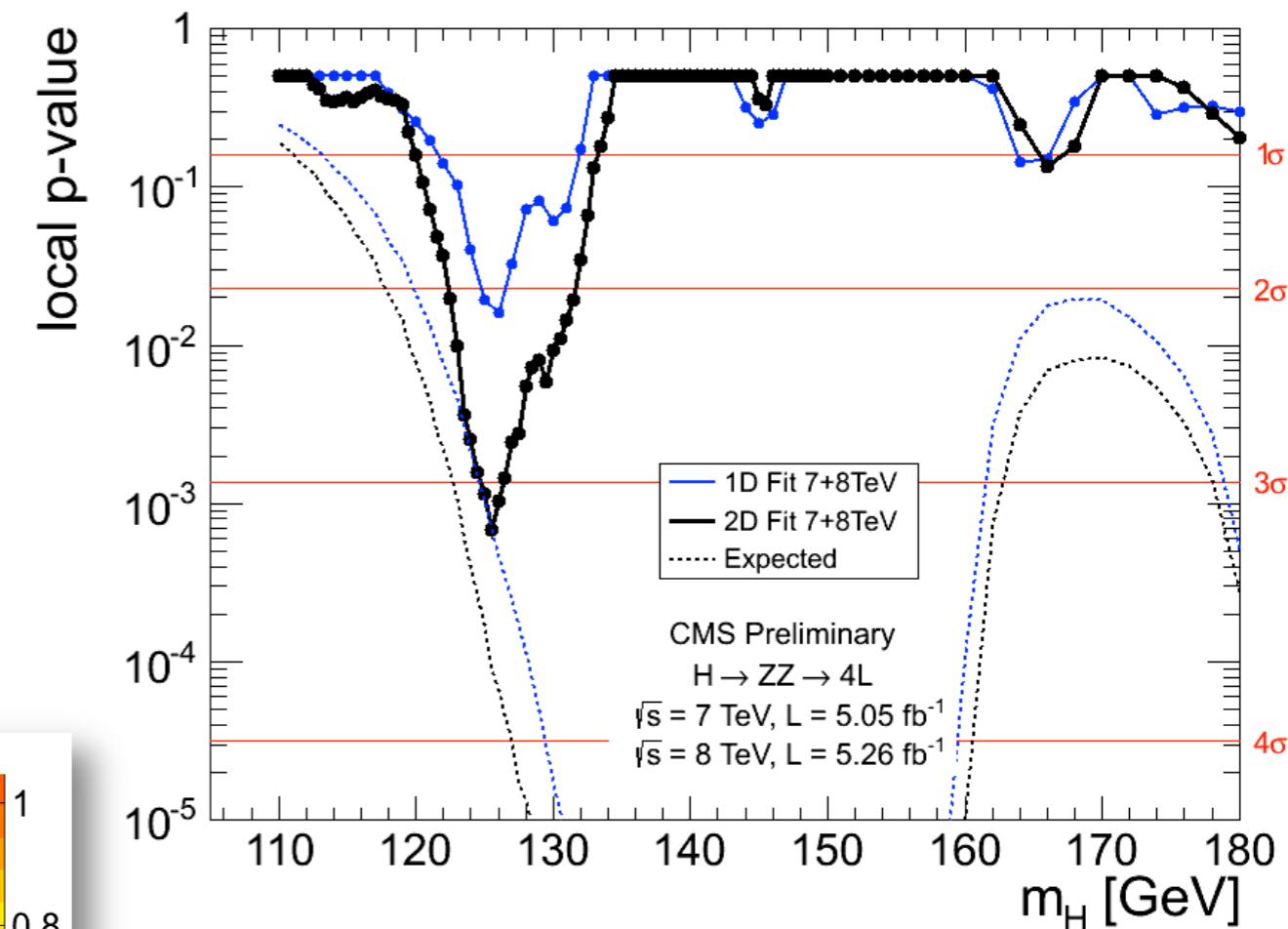
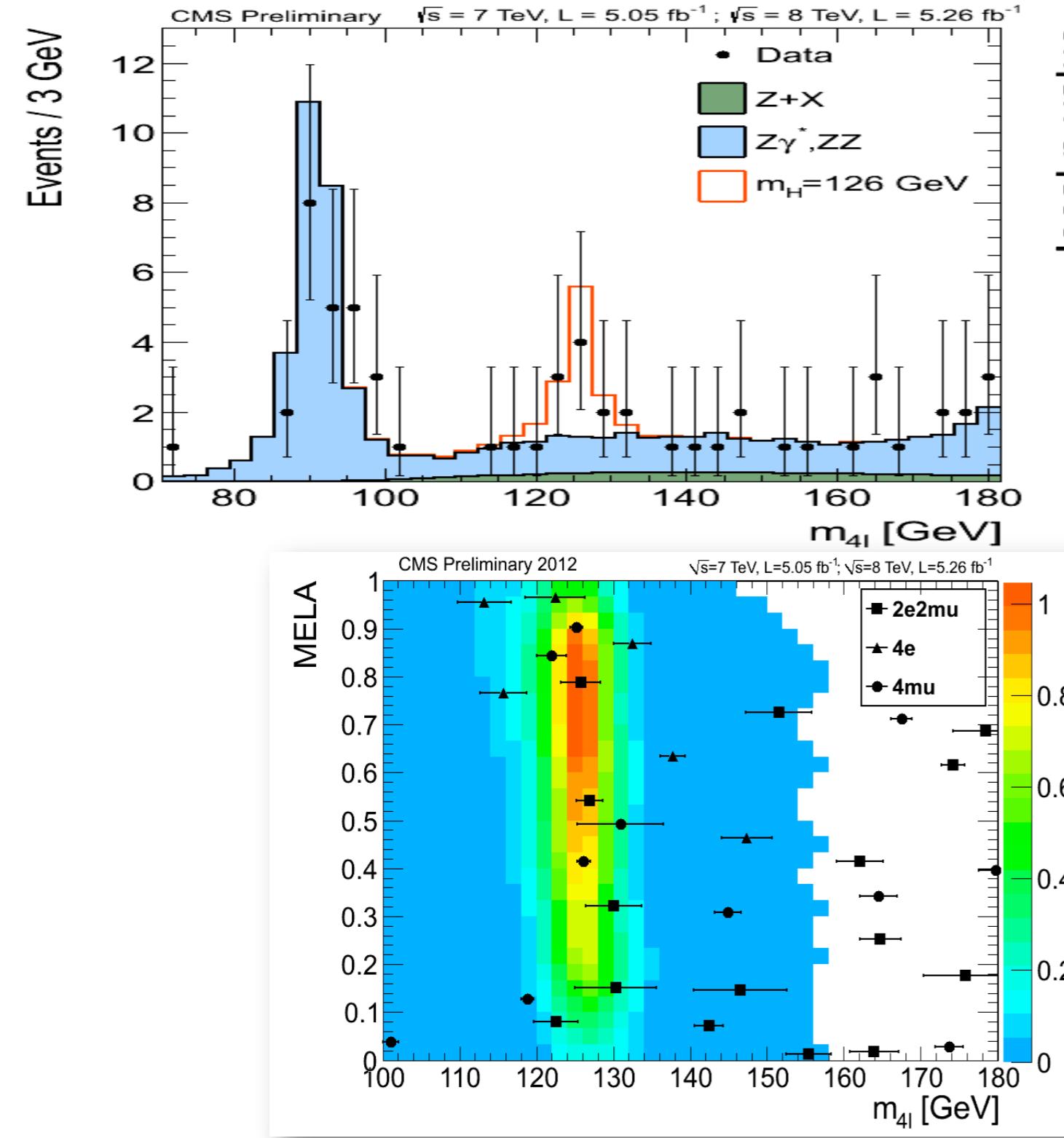
Expected exclusion at 95% CL :
121-550 GeV

Observed exclusion at 95% CL :
131-162 GeV and 172-530 GeV

Expected significance at 125.5 GeV :
3.8 σ

Observed significance at 125.5 GeV:
3.2 σ

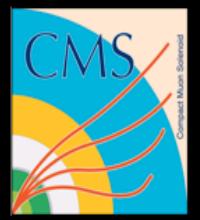
Observed local excess of events



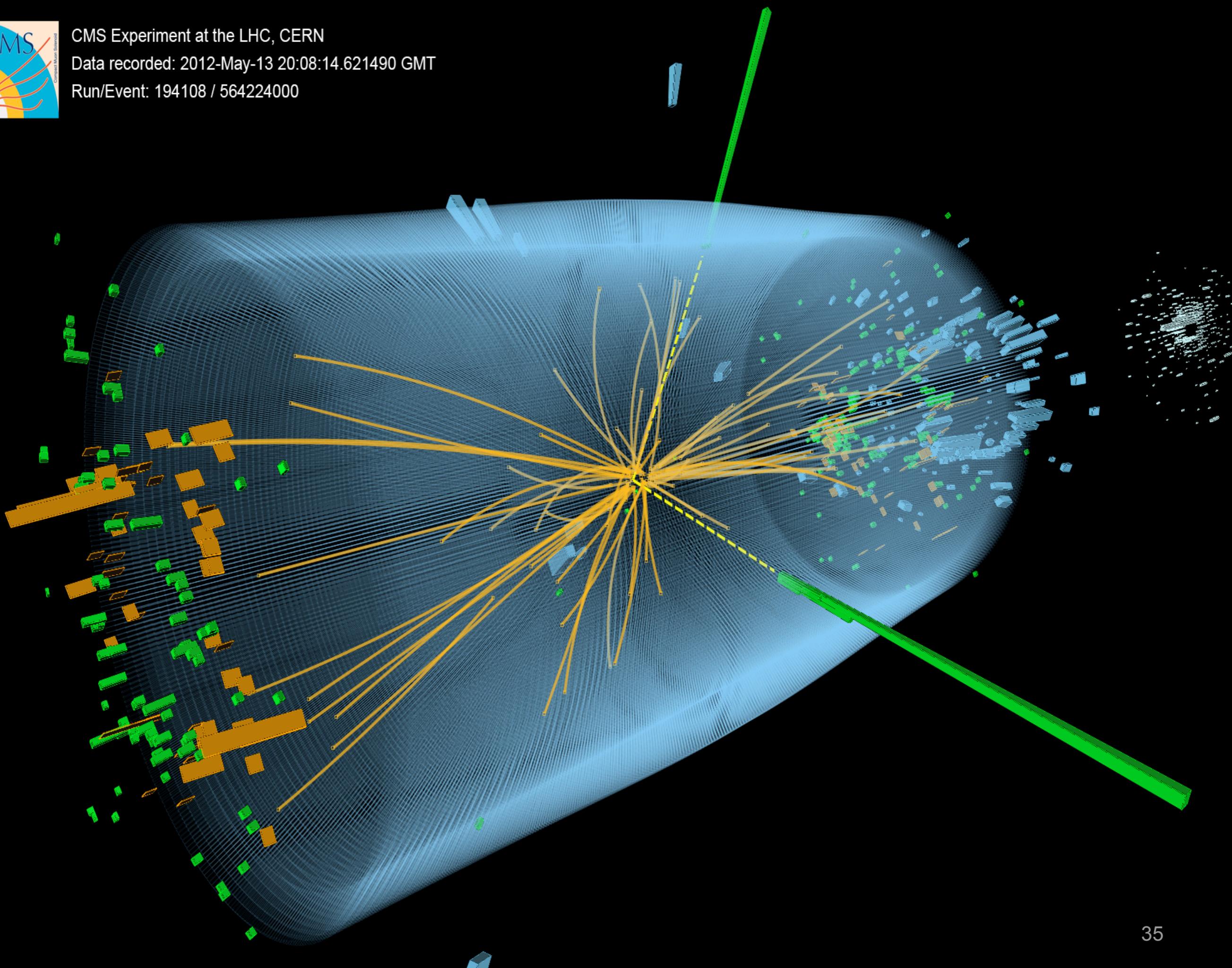
Expected significance at 125.5 GeV :
 3.8σ

Observed significance at 125.5 GeV:
 3.2σ

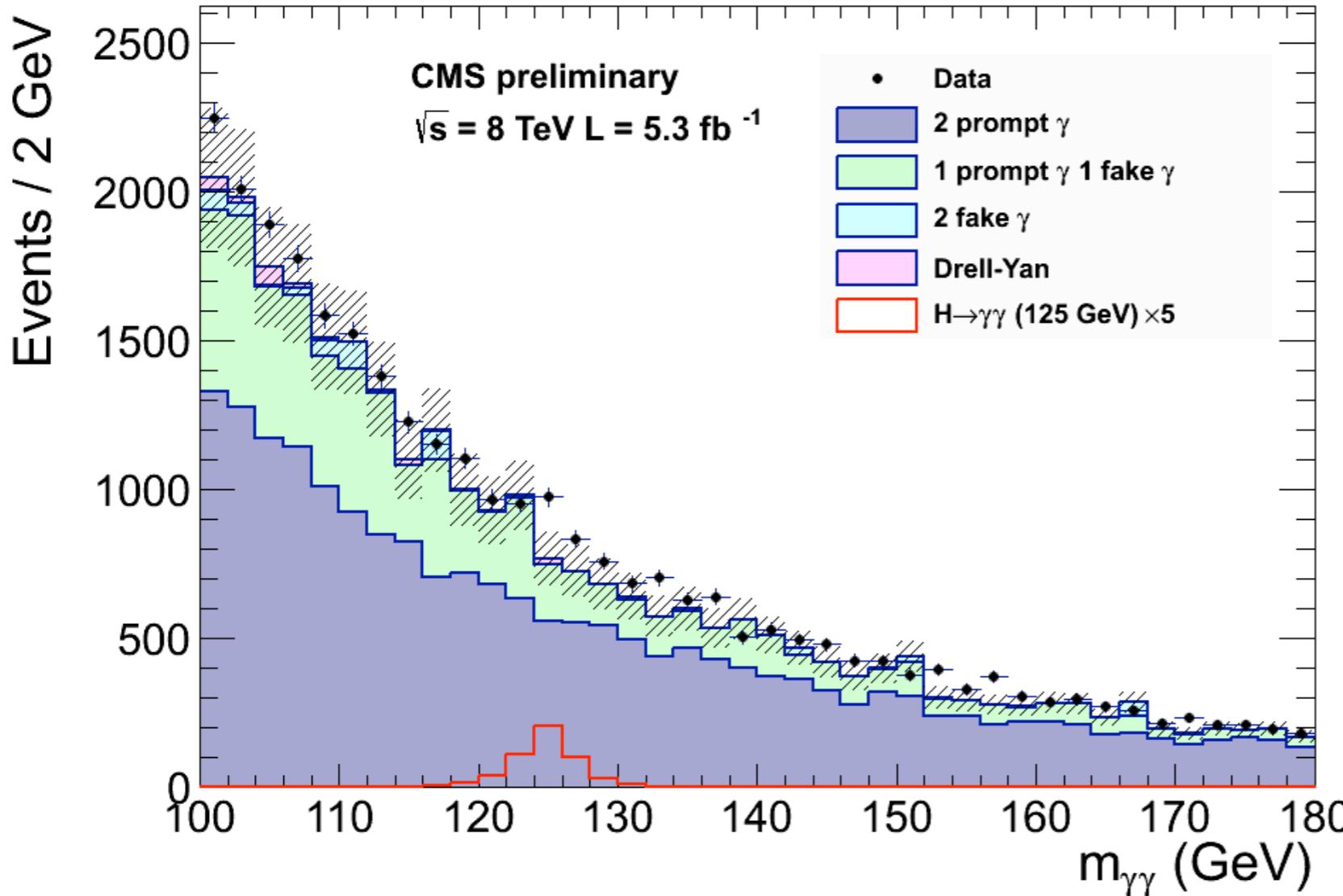
$$H\rightarrow \gamma\gamma$$



CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000



Search for a di-photon mass peak

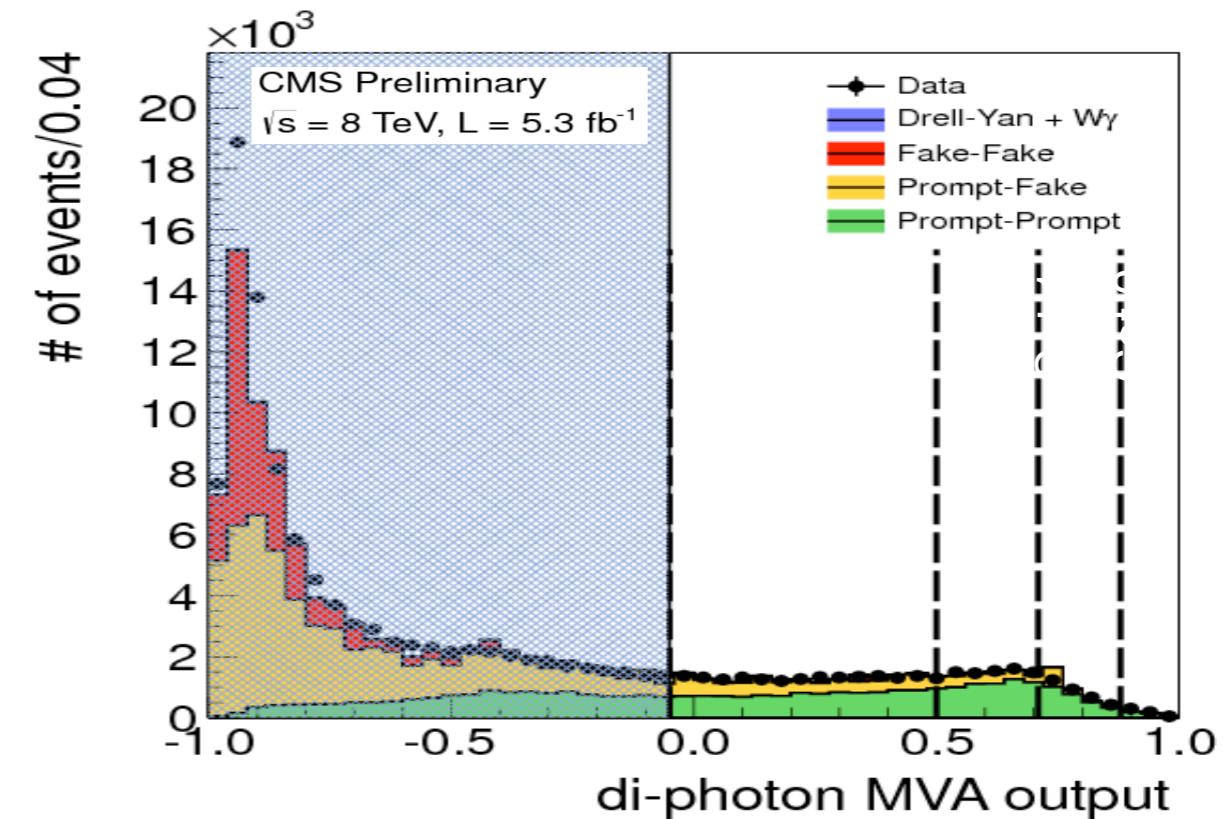
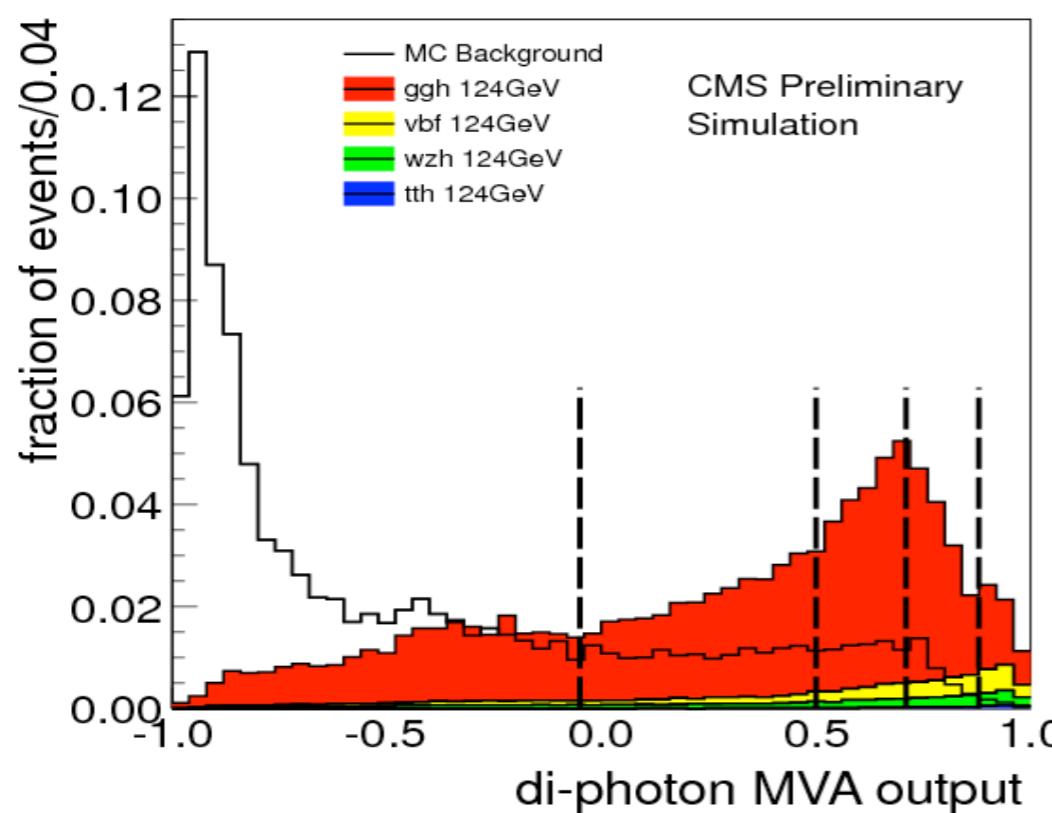


- Blind analysis in 2012
- Re-reco 2011 data into unchanged 2011 analysis
- Background MC only used for analysis optimization,
- $Z \rightarrow ee$ also to measure photon efficiencies and resolution with data

- Interaction vertex is identified using tracks from recoiling jets and underlying event plus conversions
 - correct in ~83% of cases for pileup in 2011 sample.
 - correct in ~80% of cases for pileup in 2012 sample.
- Vertex identification with a BDT
 - Input variables: Σp_t^2 , Σp_t projected onto the $\gamma\gamma$ transverse direction, p_t asymmetry and conversions

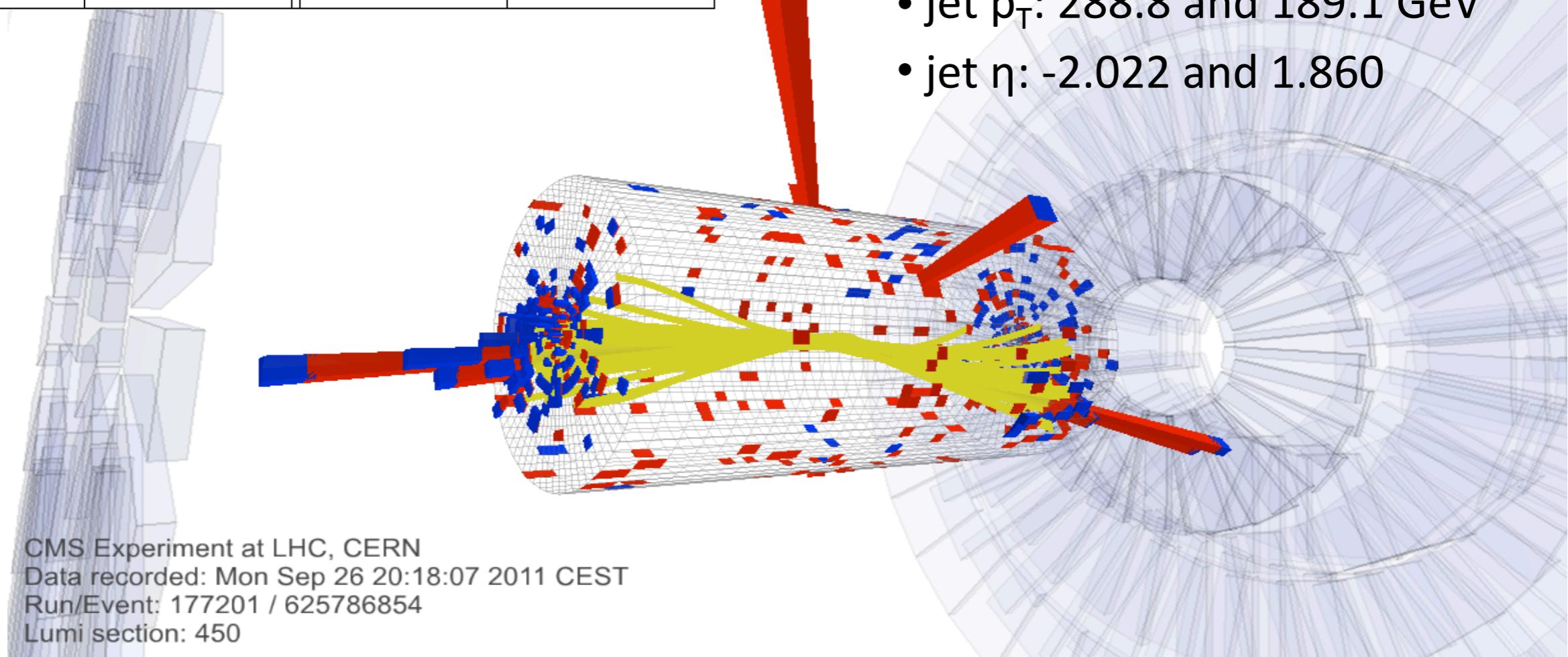
Diphoton Multivariate Analysis

- Diphoton MVA trained on signal and background MC with input variables largely independent of $m_{\gamma\gamma}$
 - Kinematics: p_T and η of each photon, and $\cos\Delta\phi$ between the 2 photons
 - Photon ID MVA output for each photon
 - per-event mass resolution and vertex probability
- Encode all relevant information on signal vs bkg. discrimination (aside from $m_{\gamma\gamma}$ itself) into a single di-photon MVA output to first order independent of $m_{\gamma\gamma}$)



Di-jet tagging

Variable	2011	2012	
		Loose	Tight
$p_T(j_1)$	$> 30 \text{ GeV}$		
$p_T(j_2)$	$> 20 \text{ GeV}$		$> 30 \text{ GeV}$
$\Delta\eta(j_1, j_2)$	> 3.5	> 3.0	
$ \eta_{\gamma\gamma} - \frac{1}{2}(\eta_{j1} + \eta_{j2}) $	< 2.5		
$\Delta\phi(jj, \gamma\gamma)$	> 2.6		
m_{jj}	$> 350 \text{ GeV}$	$> 250 \text{ GeV}$	$> 500 \text{ GeV}$

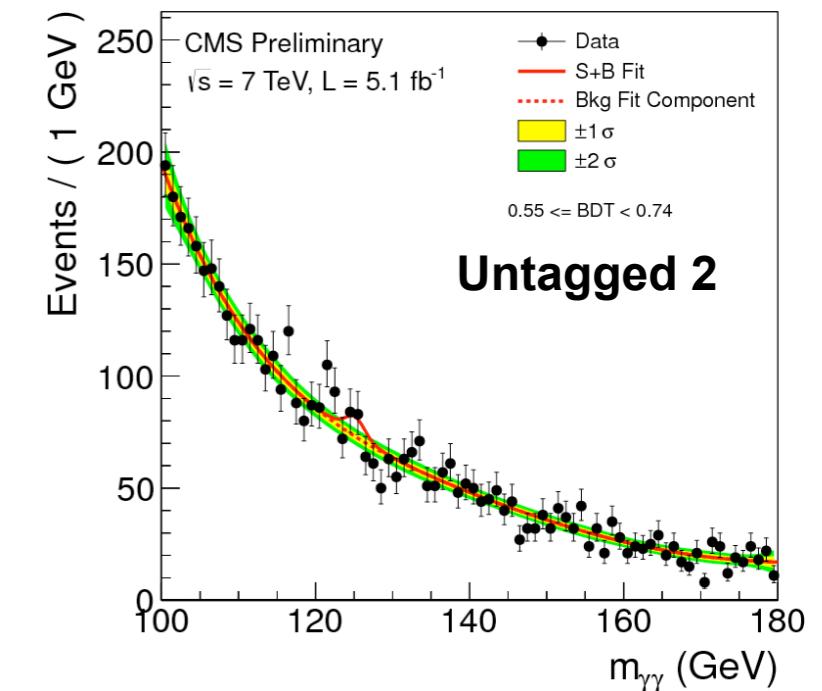
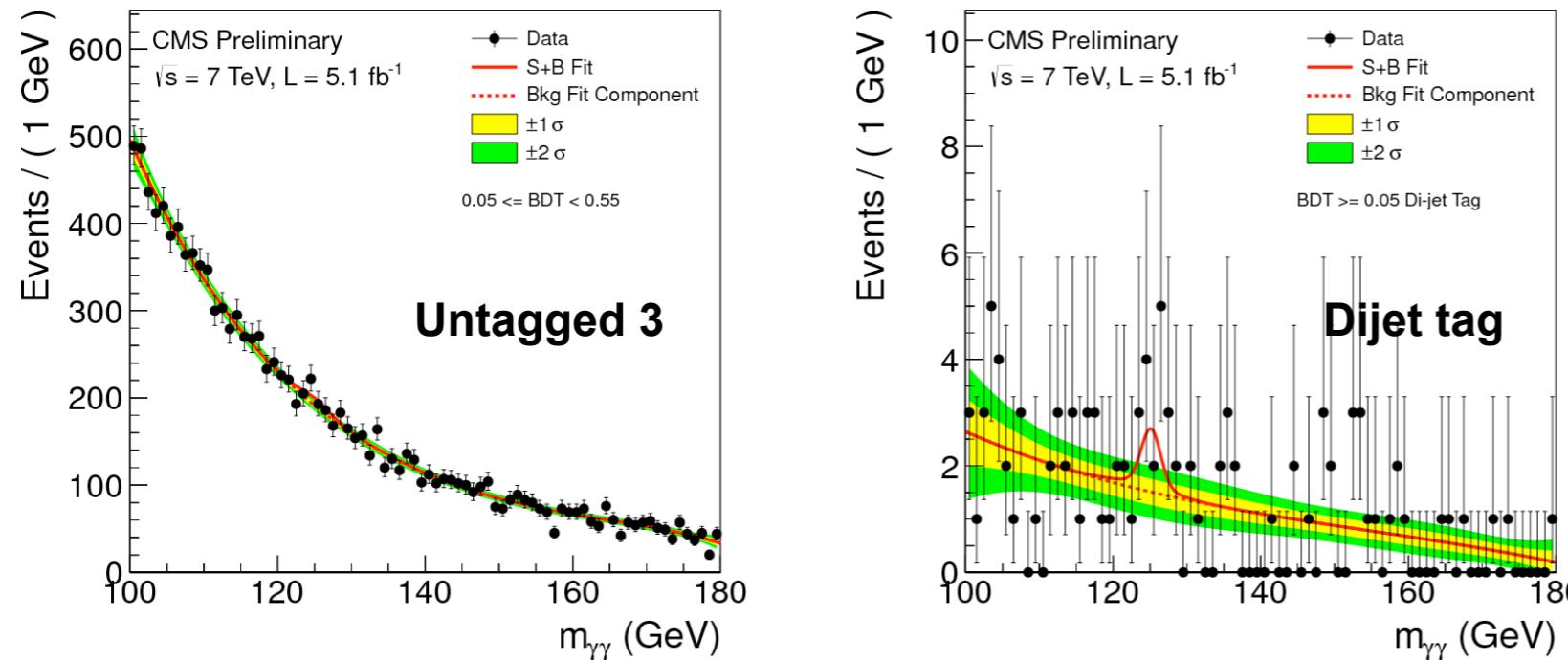
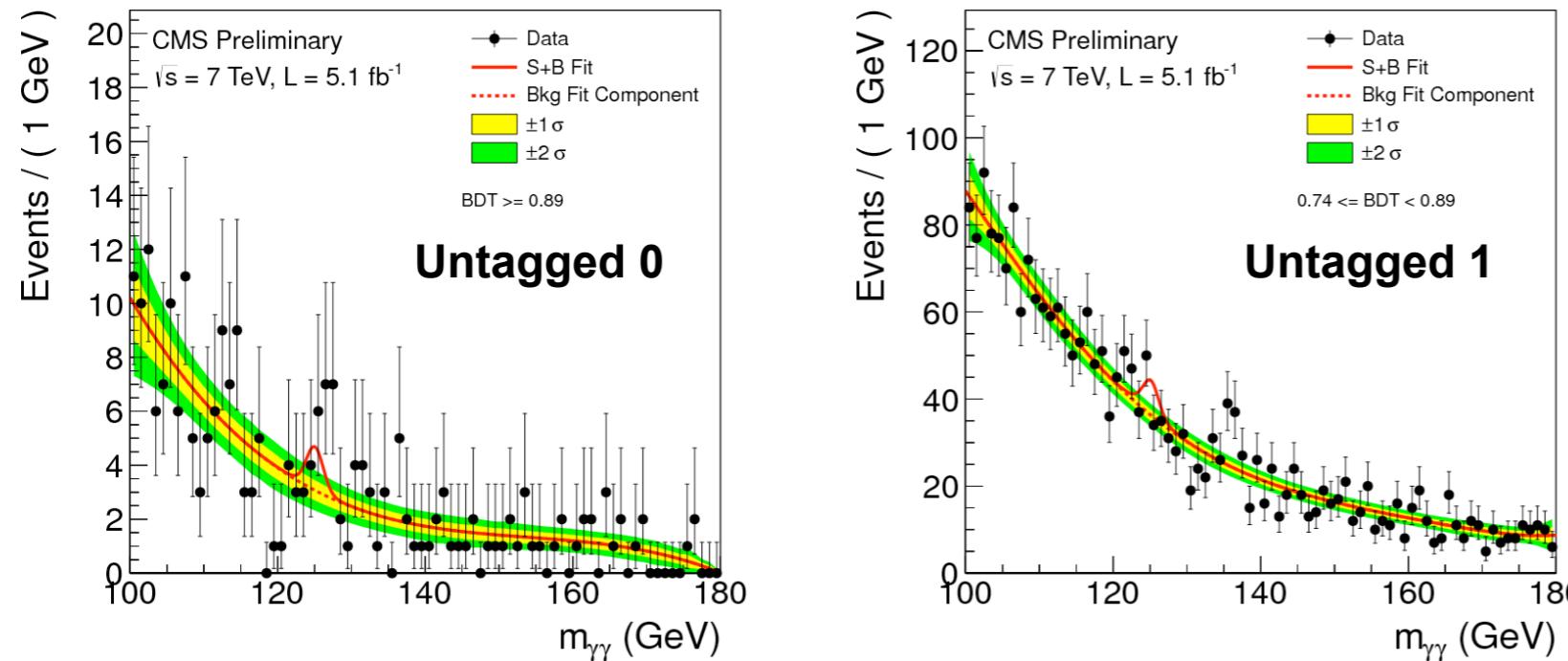
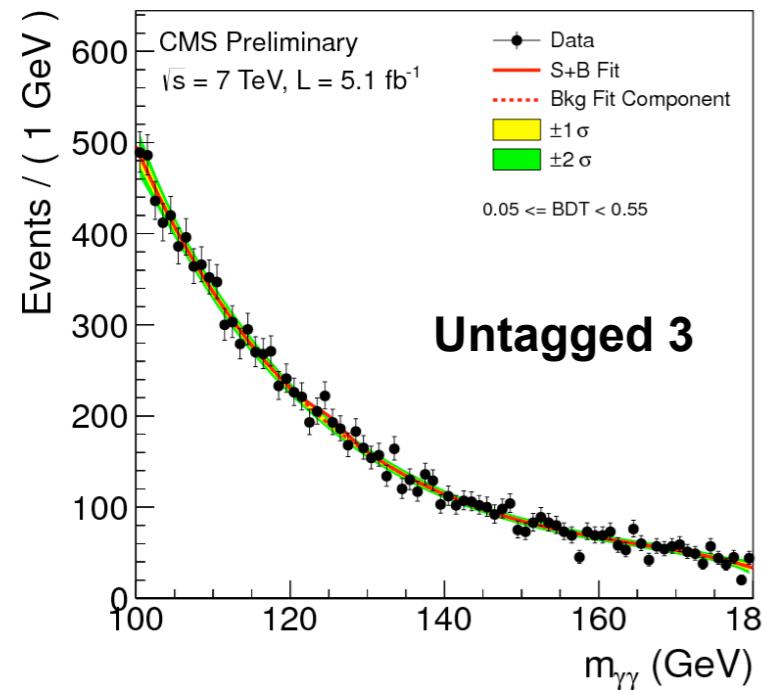
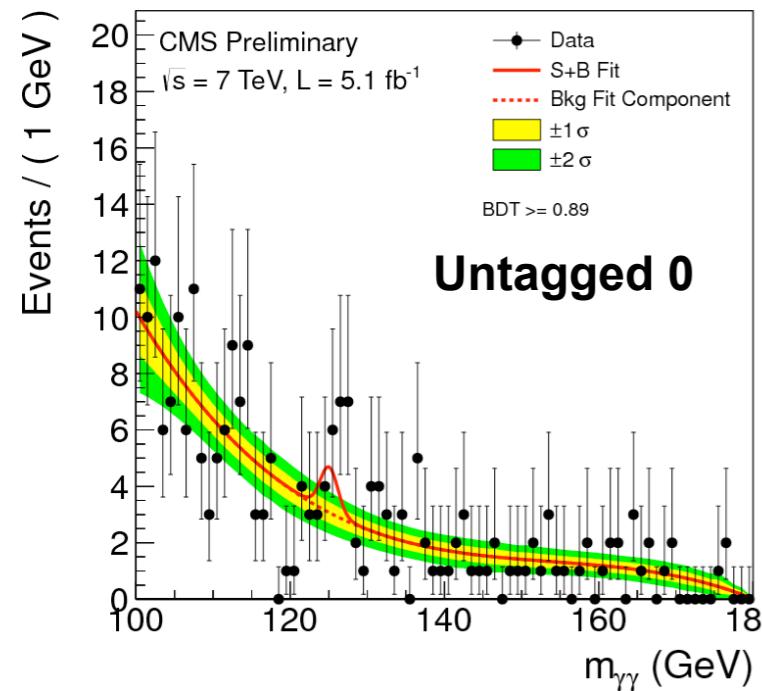


Category Performance

Expected signal and estimated background

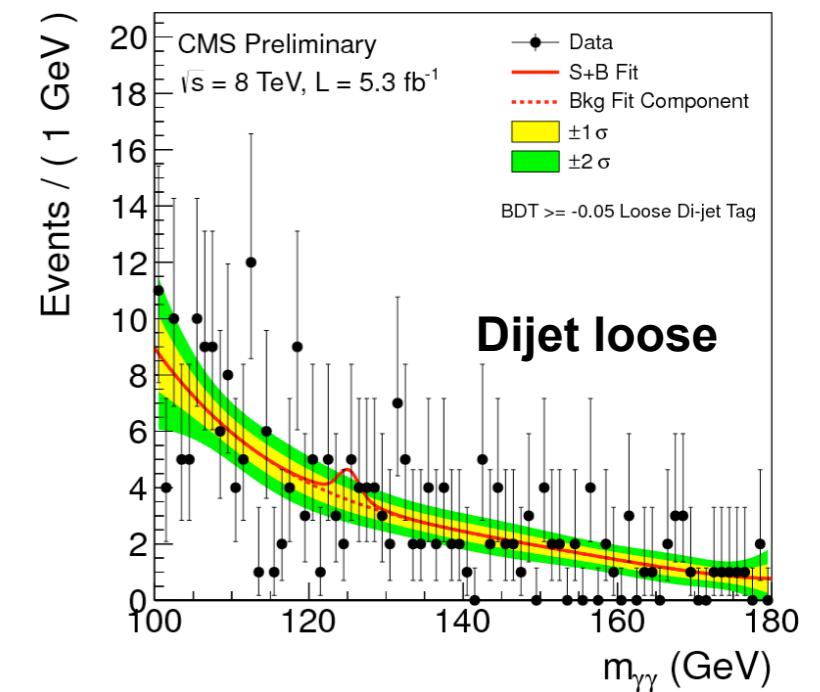
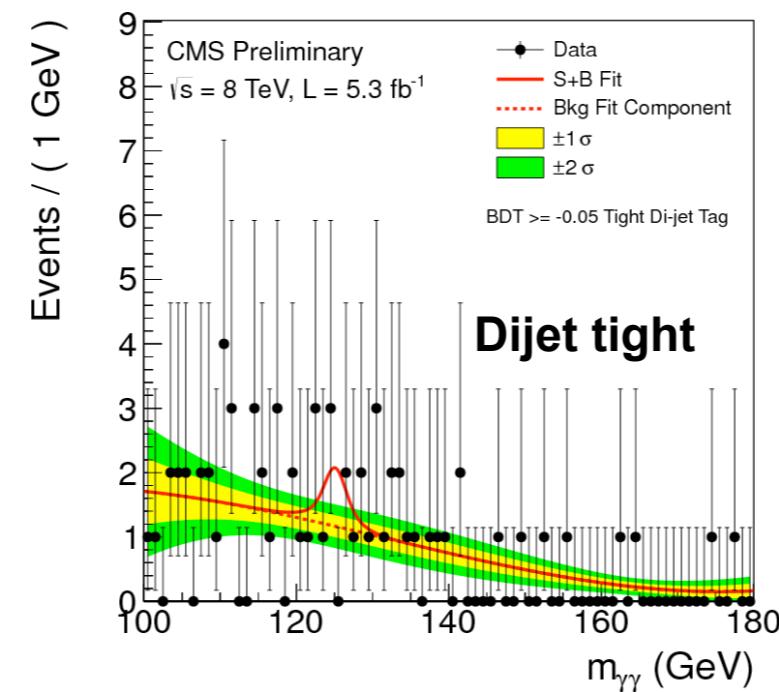
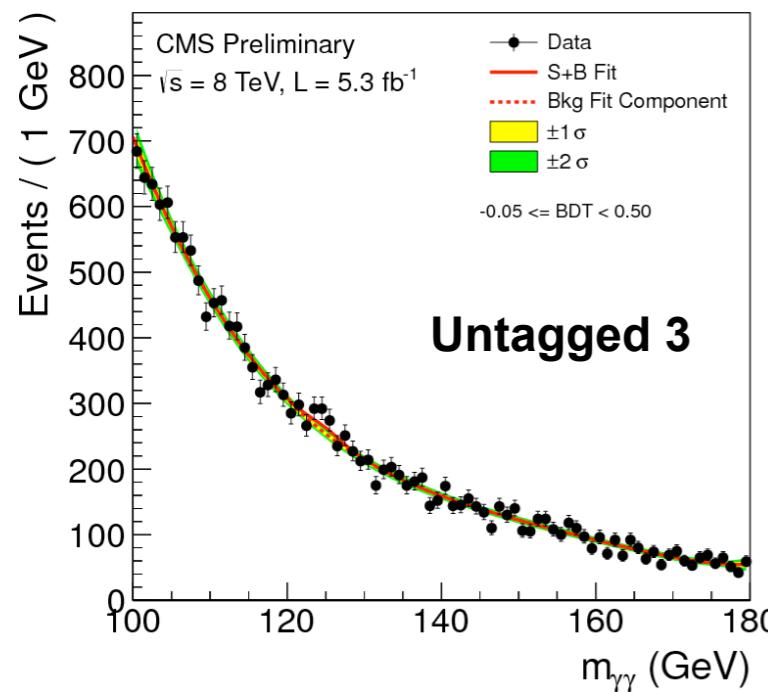
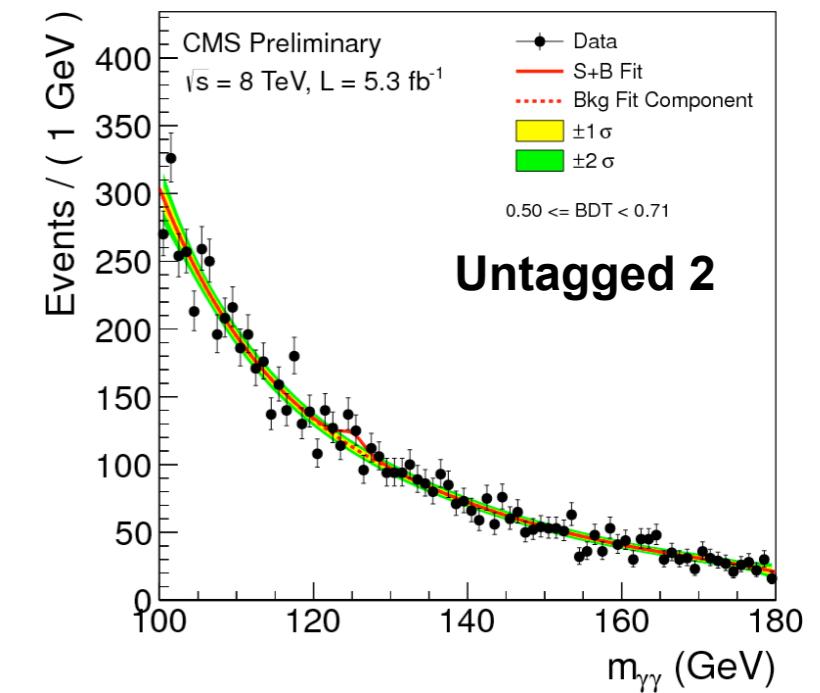
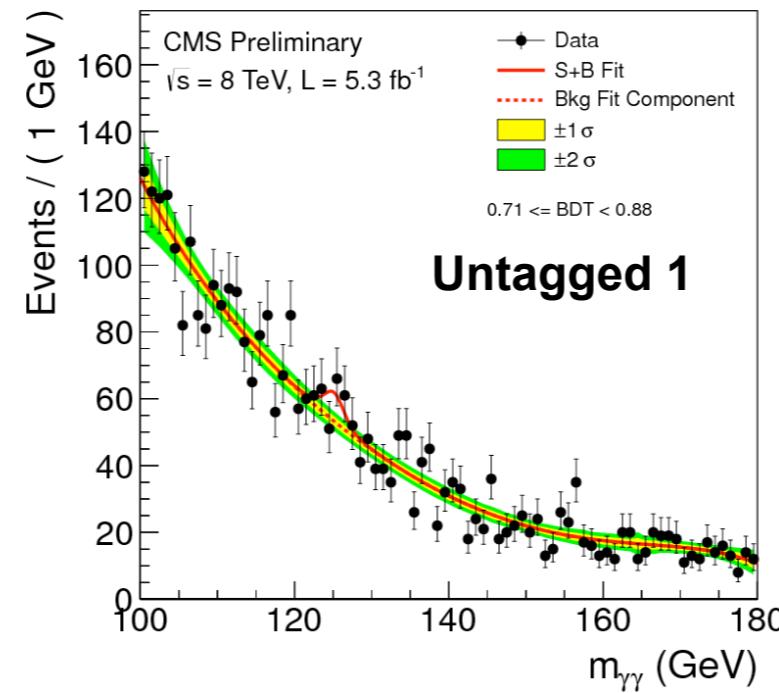
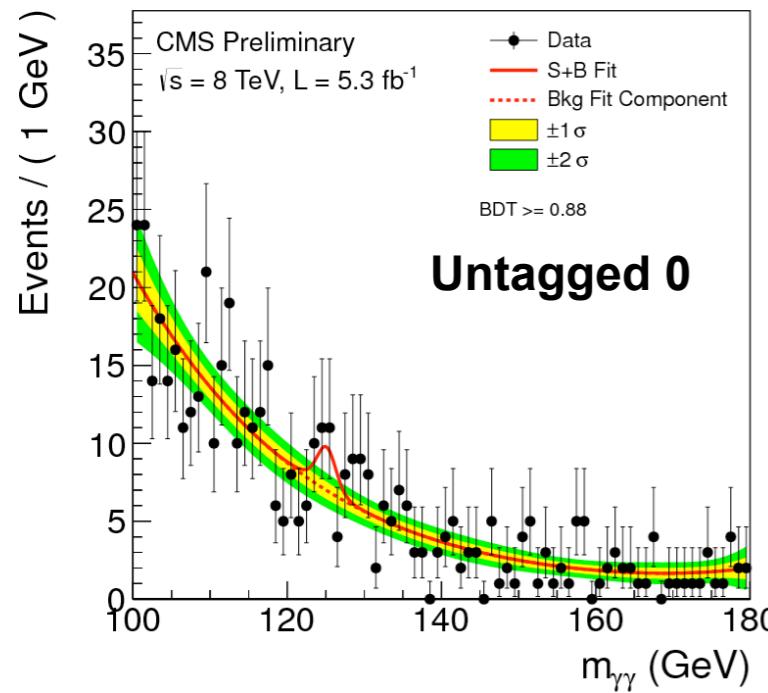
Event classes		SM Higgs boson expected signal ($m_H=125\text{ GeV}$)						Background $m_{\gamma\gamma} = 125\text{ GeV}$ (ev./GeV)	
		Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	
$7\text{ TeV } 5.1\text{ fb}^{-1}$	Untagged 0	3.2	61%	17%	19%	3%	1.21	1.14	3.3 ± 0.4
	Untagged 1	16.3	88%	6%	6%	1%	1.26	1.08	37.5 ± 1.3
	Untagged 2	21.5	91%	4%	4%	–	1.59	1.32	74.8 ± 1.9
	Untagged 3	32.8	91%	4%	4%	–	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	27%	73%	1%	–	1.73	1.37	1.7 ± 0.2
	Untagged 0	6.1	68%	12%	16%	4%	1.38	1.23	7.4 ± 0.6
$8\text{ TeV } 5.3\text{ fb}^{-1}$	Untagged 1	21.0	88%	6%	6%	1%	1.53	1.31	54.7 ± 1.5
	Untagged 2	30.2	92%	4%	3%	–	1.94	1.55	115.2 ± 2.3
	Untagged 3	40.0	92%	4%	4%	–	2.86	2.35	256.5 ± 3.4
	Dijet tight	2.6	23%	77%	–	–	2.06	1.57	1.3 ± 0.2
	Dijet loose	3.0	53%	45%	2%	–	1.95	1.48	3.7 ± 0.4

7 TeV Mass Distribution in Categories

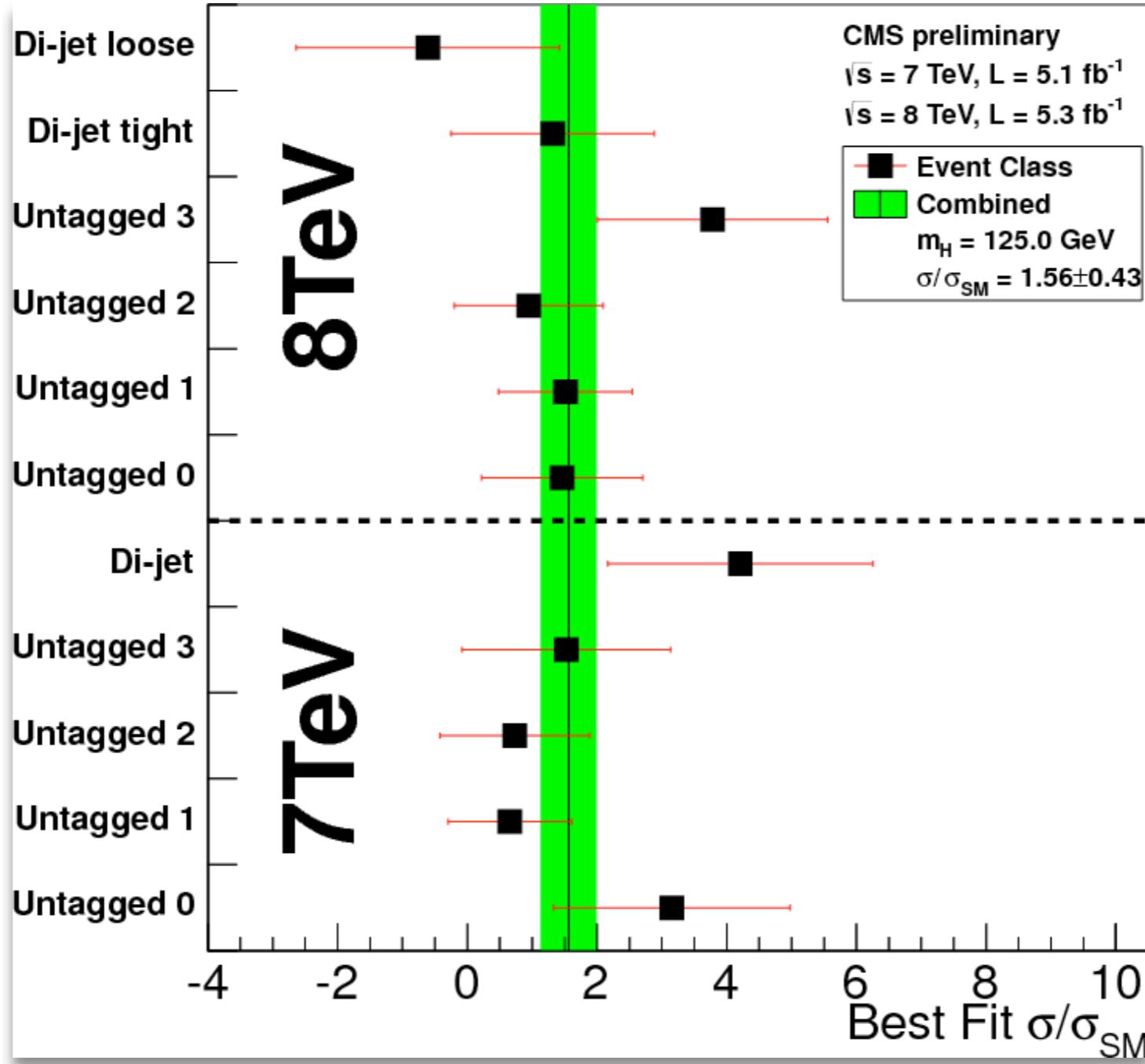


- Background model is entirely from data.
- Fit to mass distribution in each category with polynomial functions (3rd to 5th degree)
 - keep bias below 20% of fit error.
 - causes some loss of performance due to number of parameters in fit function.

8 TeV Mass Distribution in Categories

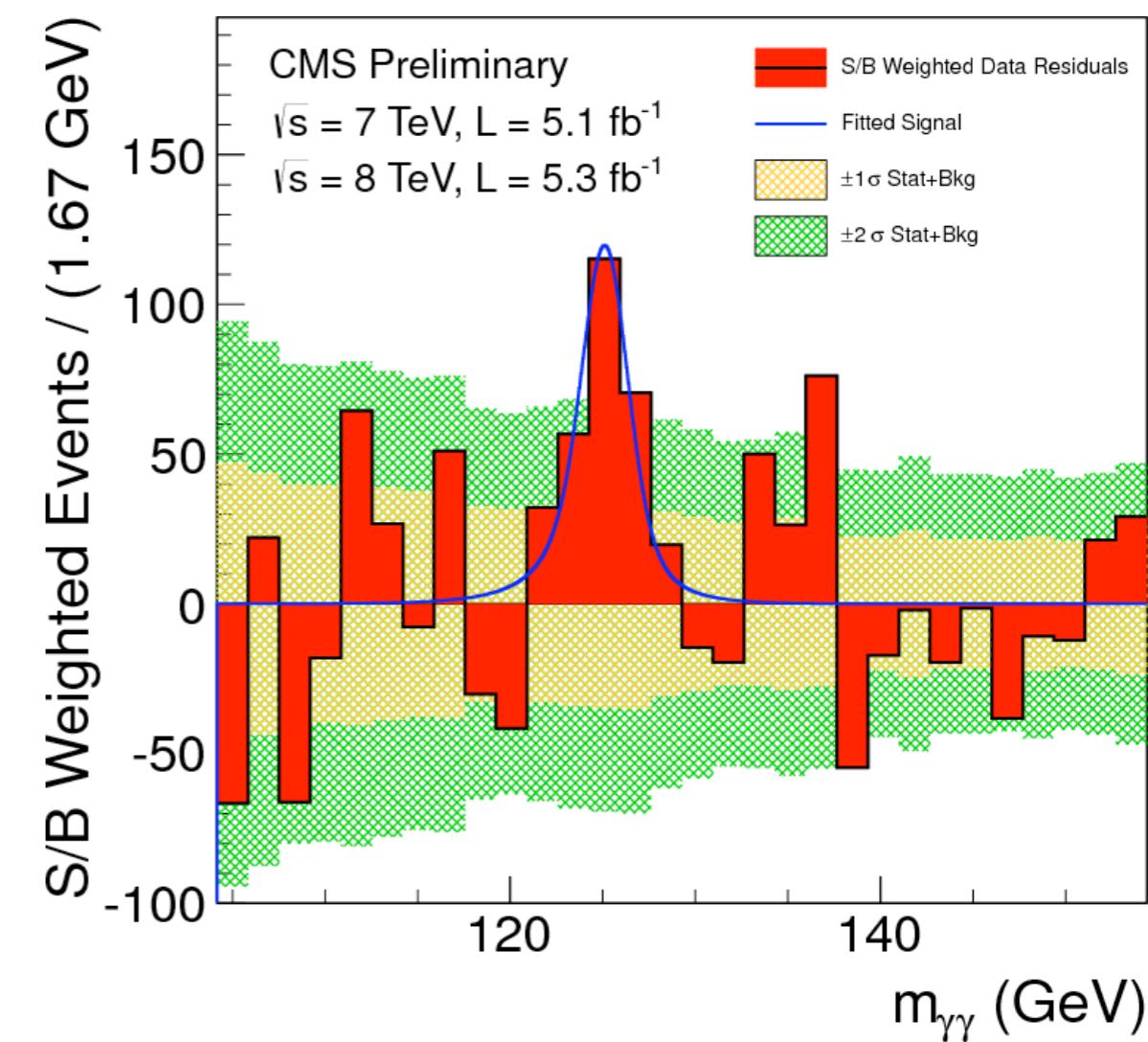
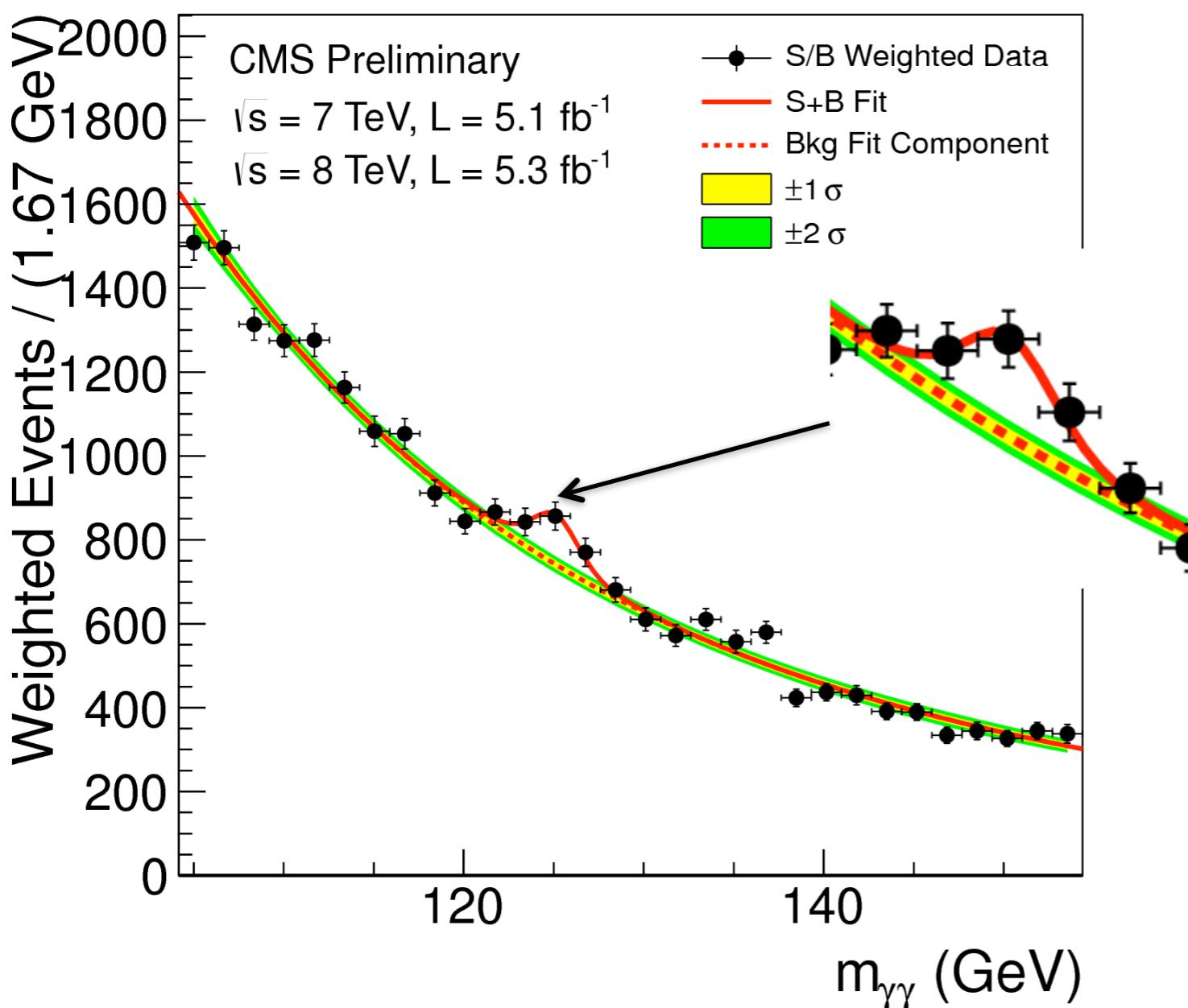


Fit Results in Categories

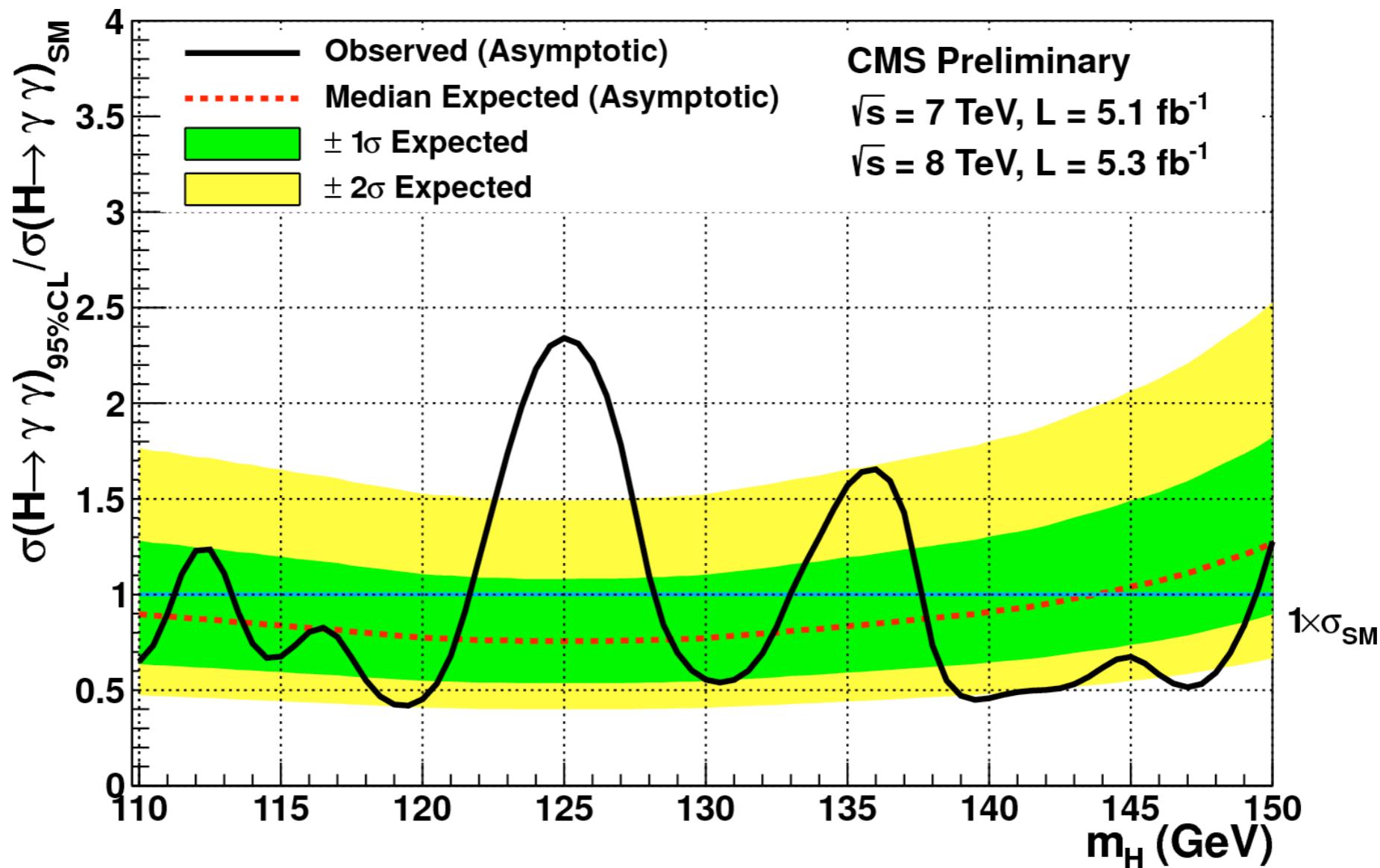


S/B Weighted Mass Distribution

- Sum of mass distributions for each event class, weighted by S/B
 - B is integral of background model over a constant signal fraction interval

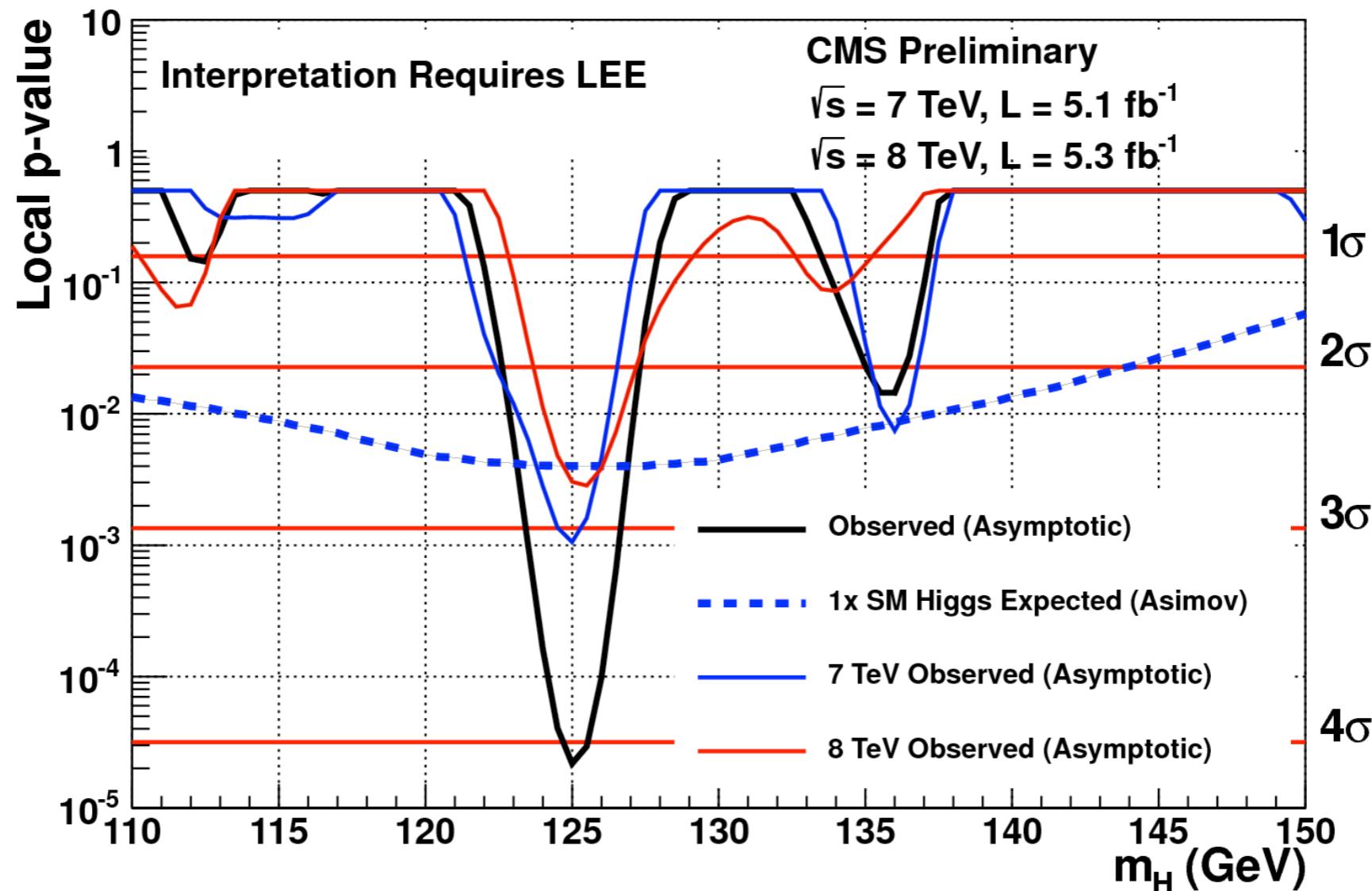


95% CL Exclusion for SM Higgs



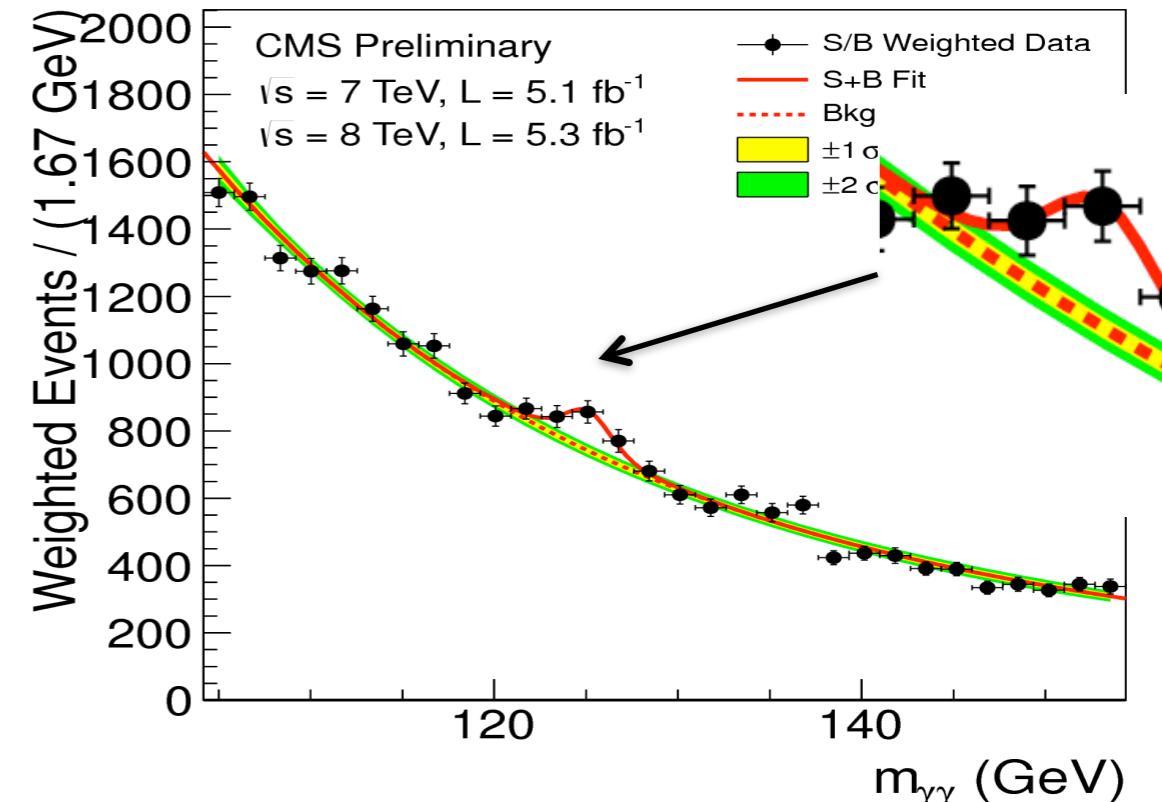
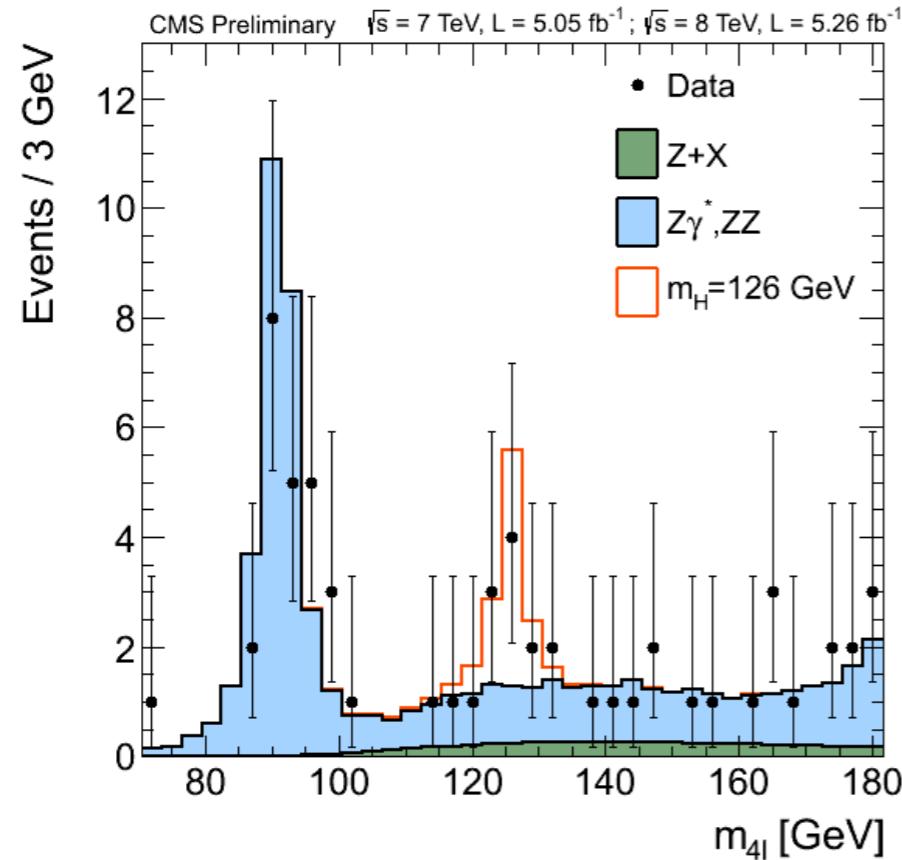
- Expected 95% CL exclusion 0.76 times SM at 125 GeV
- Large range with expected excursion below σ_{SM}

P-Values

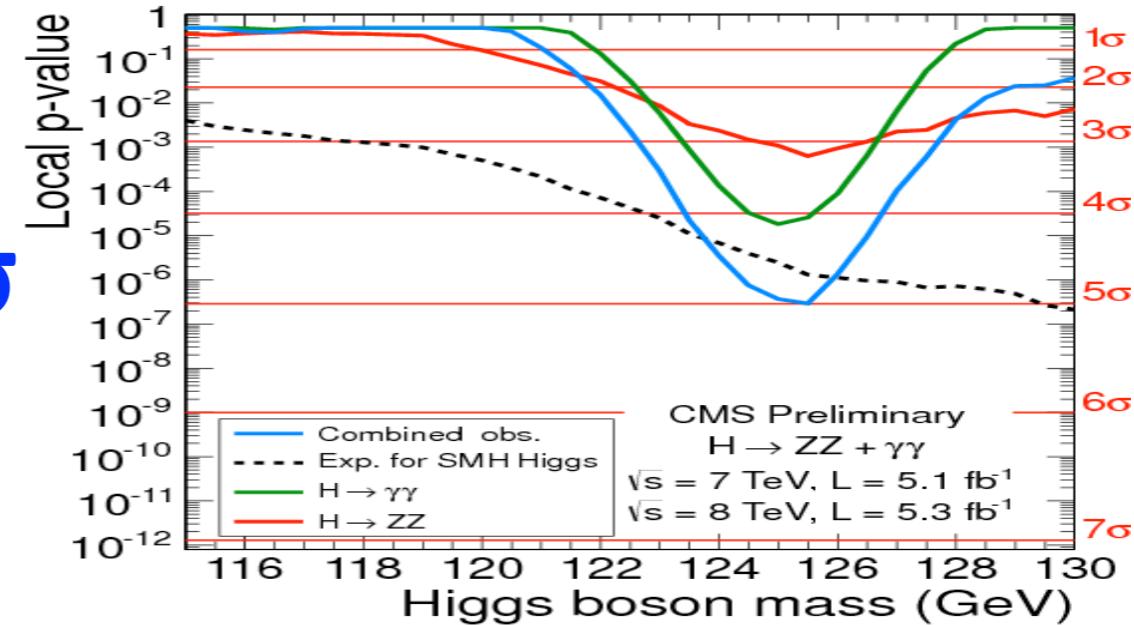


- Minimum local p-value at 125 GeV with significance of 4.1σ

Two channels ZZ and 2gamma combined

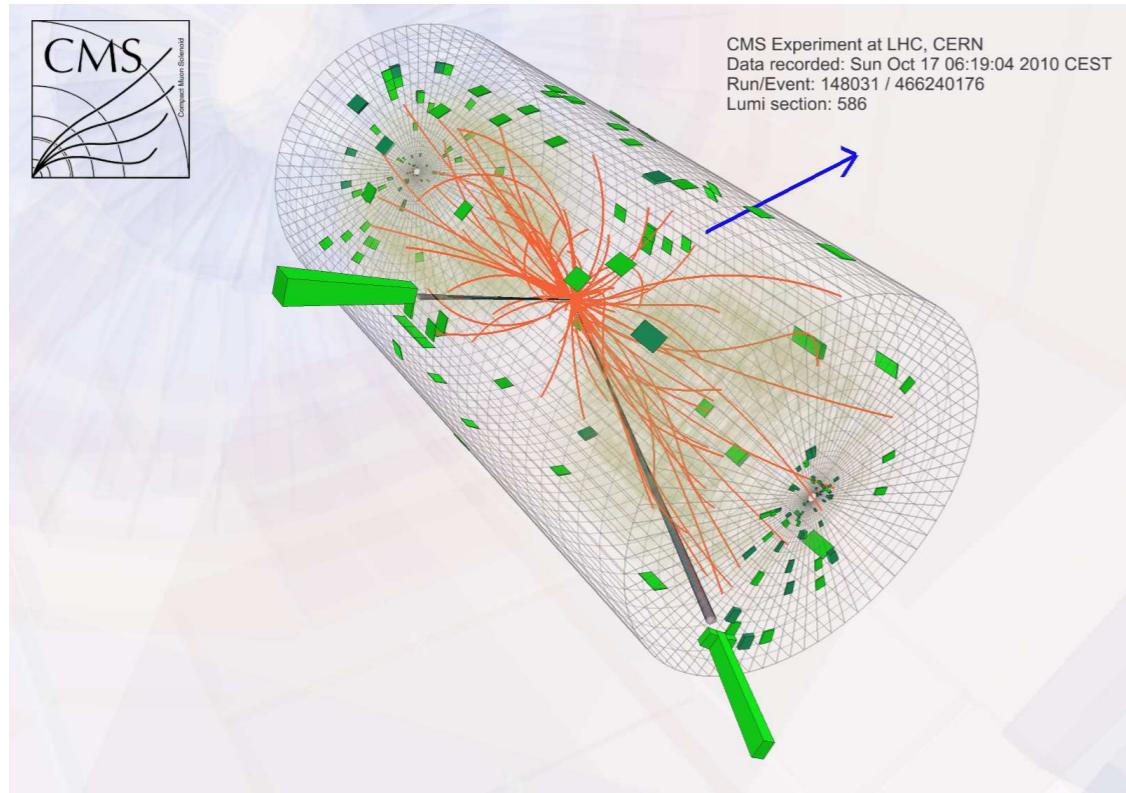


- Comb. significance: 5.0σ
- Expected 4.7σ



$$H \rightarrow WW^{(*)}$$

$$\text{Higgs} \rightarrow WW^{(*)} \rightarrow (\ell_1^- \bar{\nu})(\ell_2^+ \nu)$$

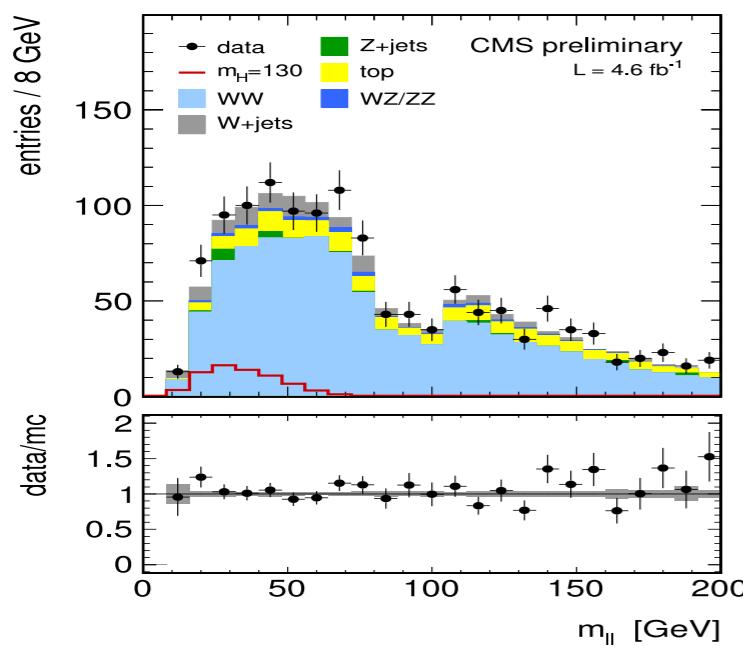


- Partial reconstruction

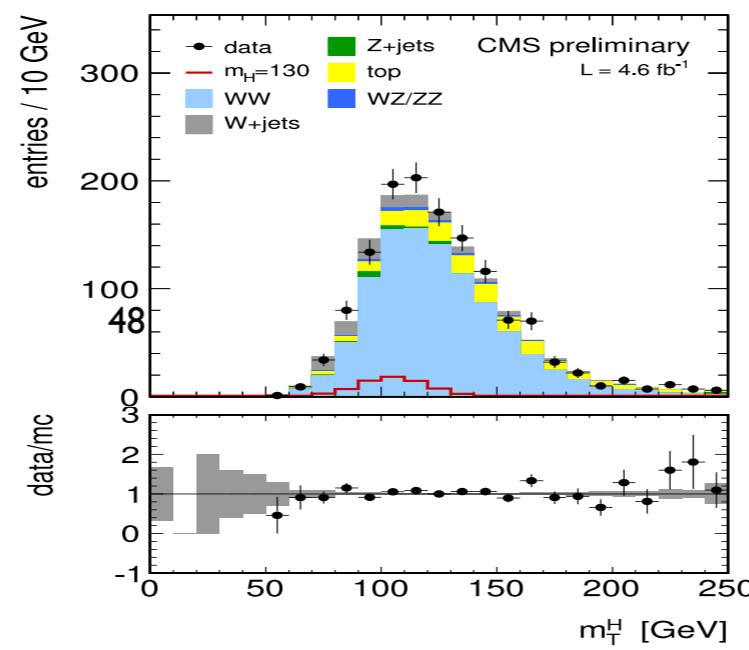
$|m_{\ell\ell} - m_Z| > 15 \text{ GeV}$
 projected ($\perp \ell$) MET $> 40 \text{ GeV} (\ell\ell)$
 $> 20 \text{ GeV} (e\mu)$

- Require 0, 1, and 2 (VBF) jets
- Reject top: soft μ and b -tag veto

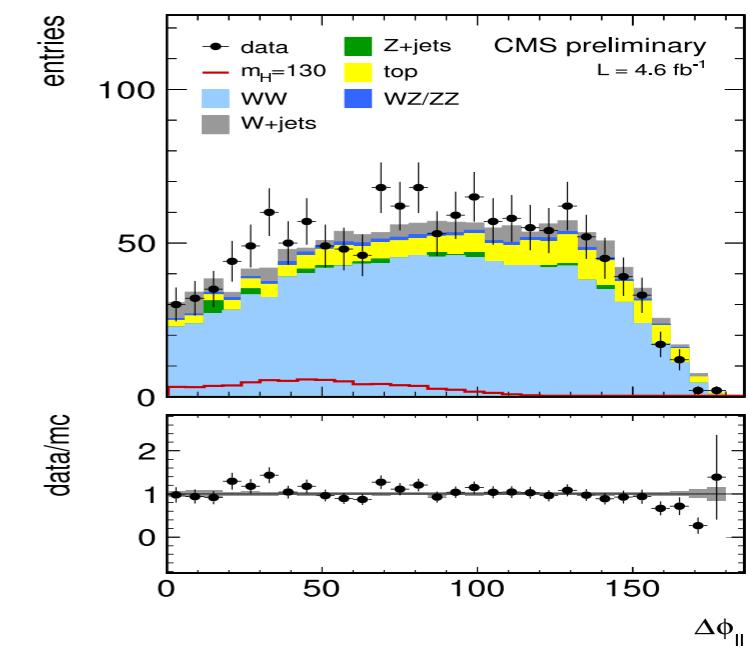
130 GeV: $m_{\ell\ell} < 45 \text{ GeV}$



$80 < m_T < 125 \text{ GeV}$

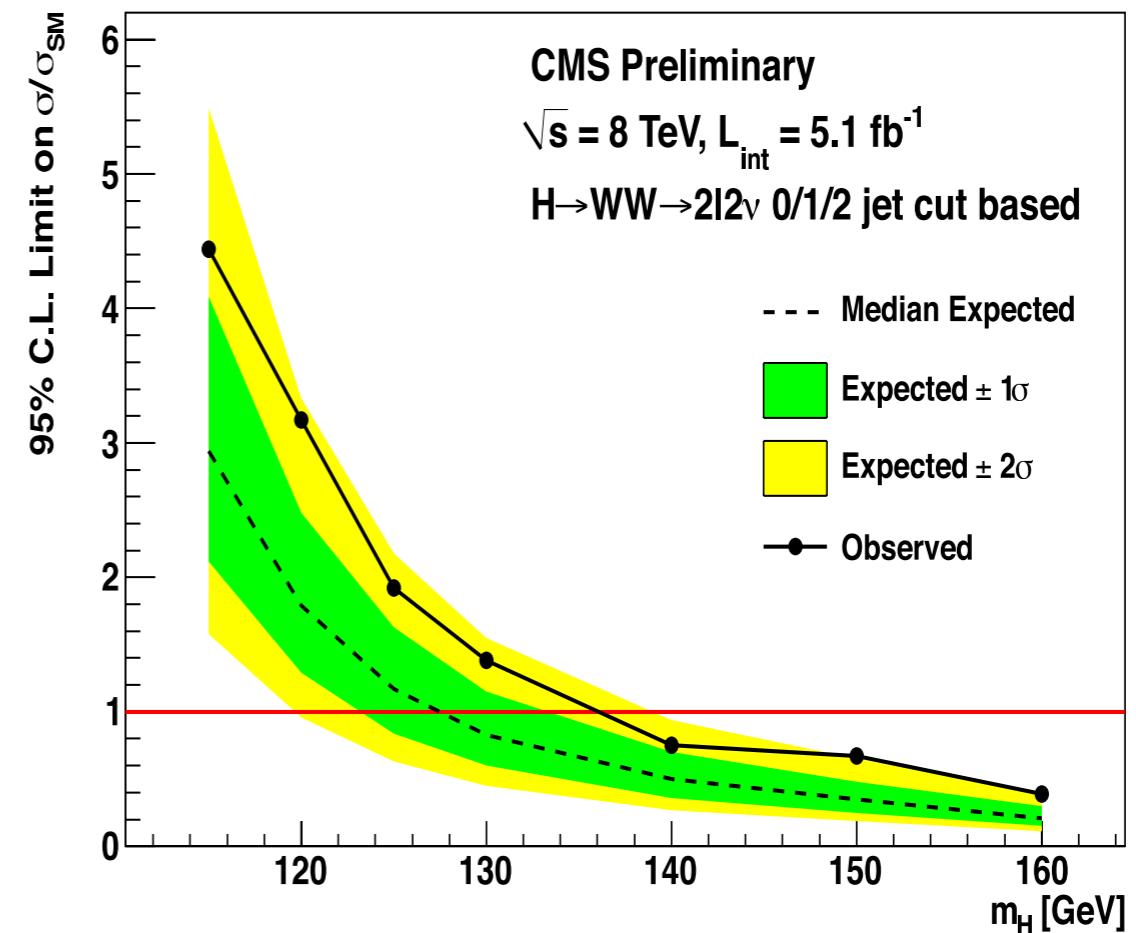
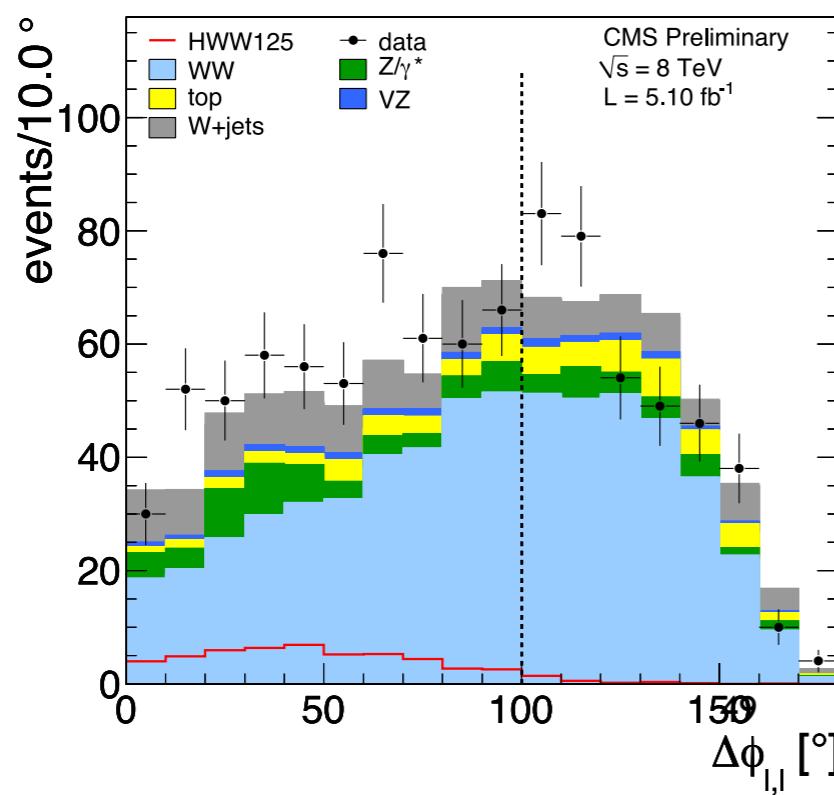


$\Delta\phi_{\ell\ell} < \pi/2$



Higgs $\rightarrow WW^{(*)} \rightarrow (\ell^-\bar{\nu})(\ell^+\nu)$

- 7 TeV data analysis unchanged (BDT, shape)
- 8 TeV data analysis – cut based
 - shape fit in development
 - excess consistent with ZZ

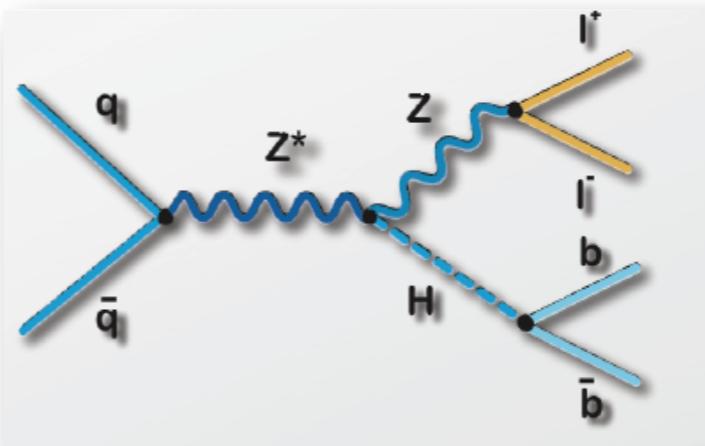


- $R_{WW/ZZ} = 0.9^{+1.1}_{-0.6}$

$$H \rightarrow b\overline{b}$$

Analysis Strategy

Associated Production
=> final states with
leptons, MET and b-jets



5 channels

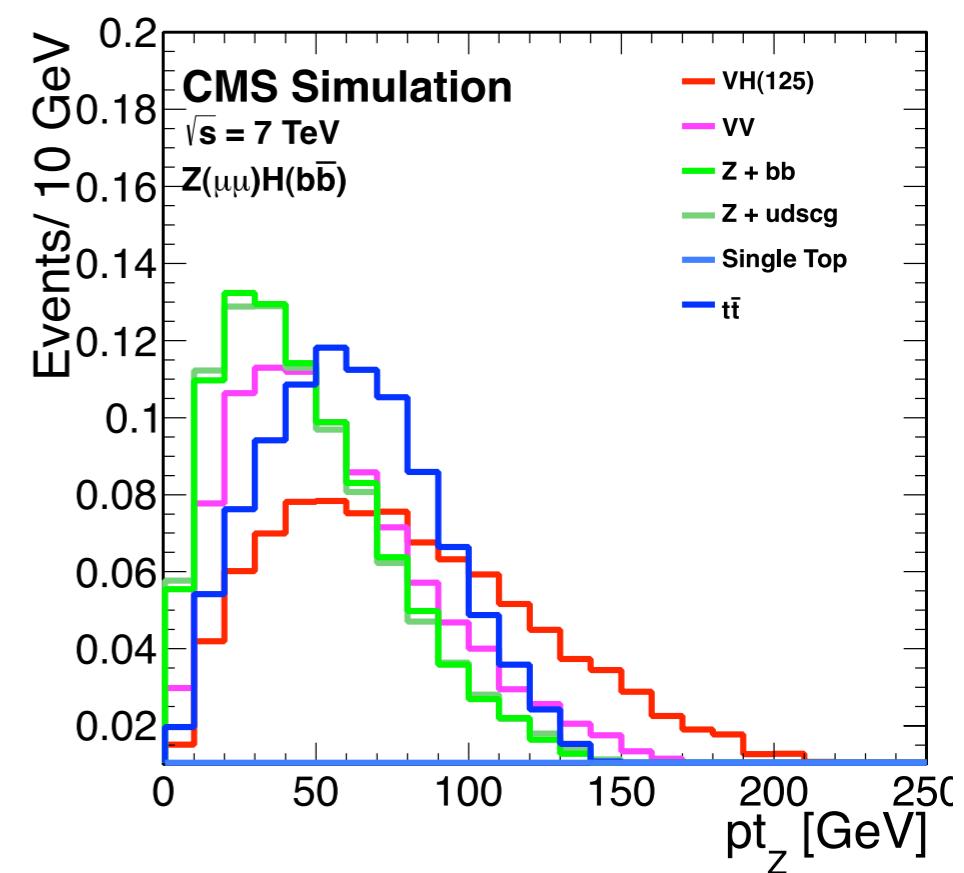
- $Z(l\bar{l})H(bb)$
- $Z(\nu\bar{\nu})H(bb)$
- $W(l\nu)H(bb)$

Reducible Backgrounds:
QCD, top, W/Z+ light jets

Less reducible:
 $V+bb$, $ZZ(bb)$, $WZ(bb)$

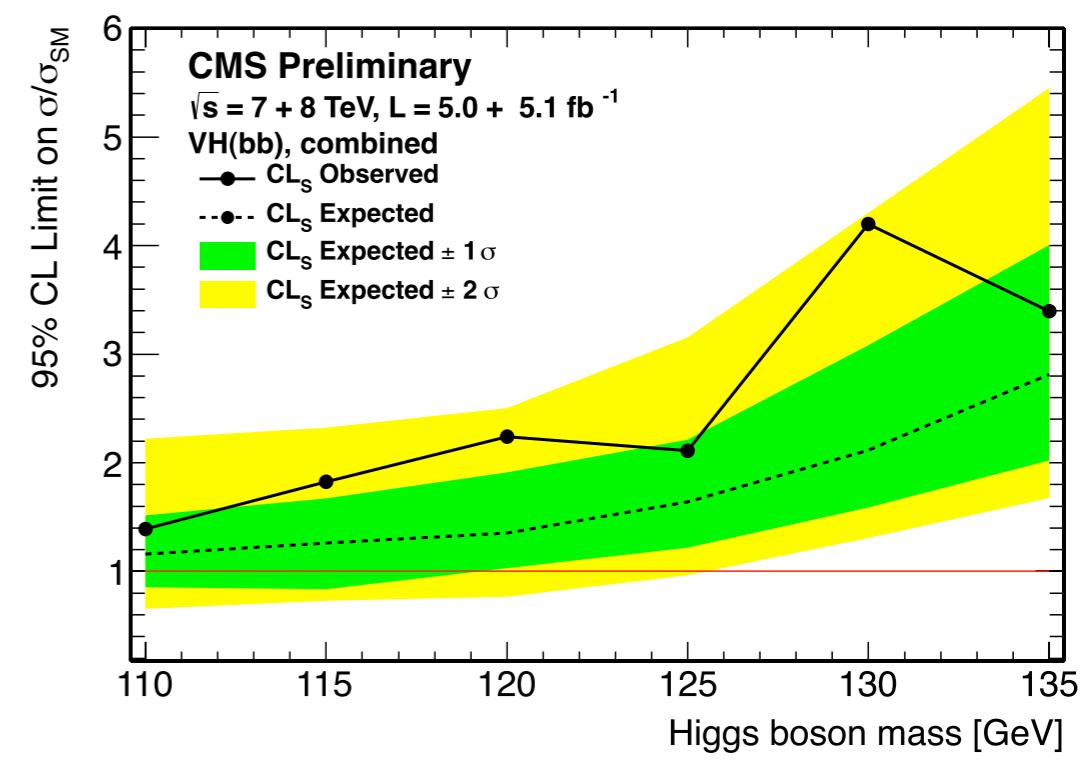
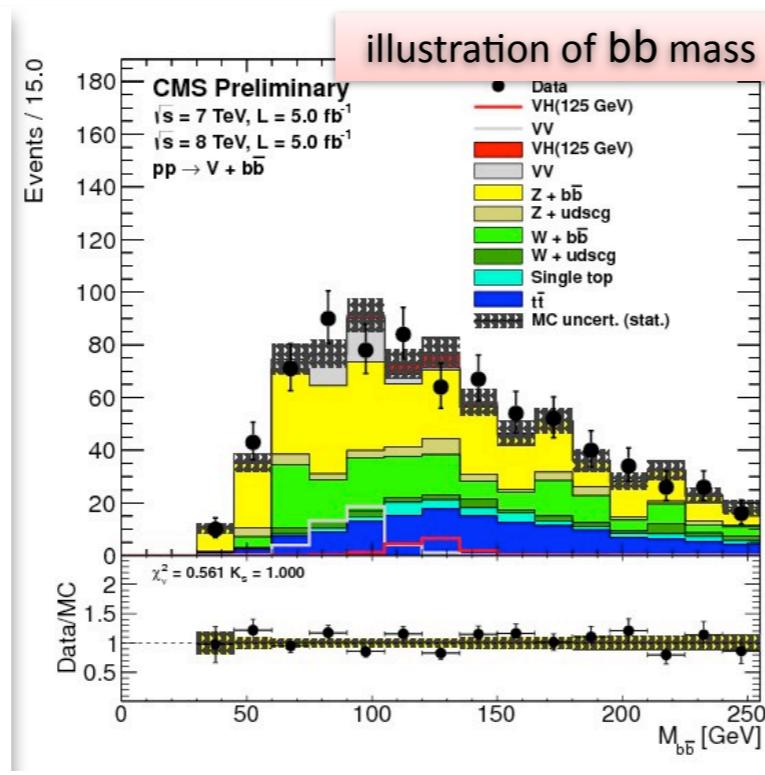
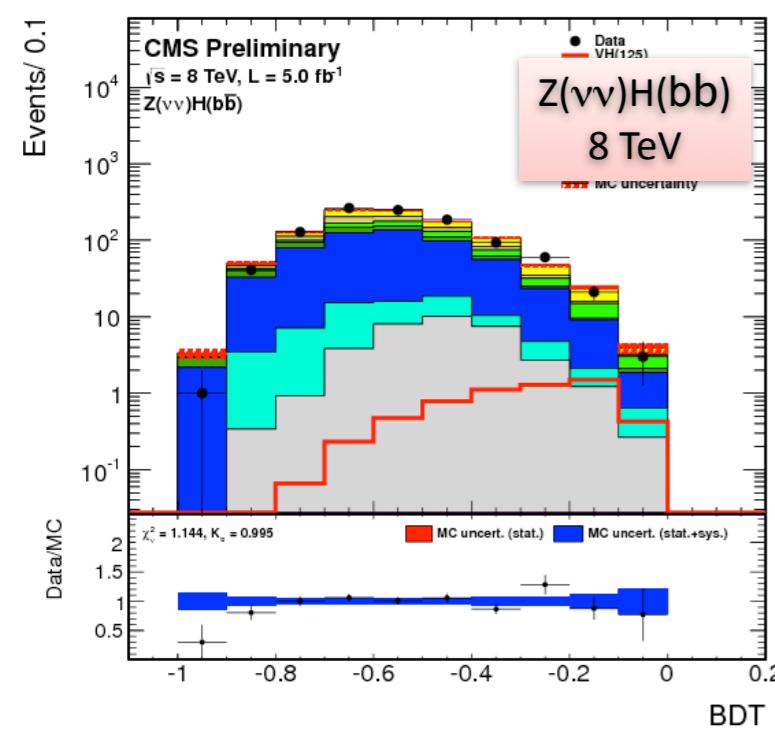
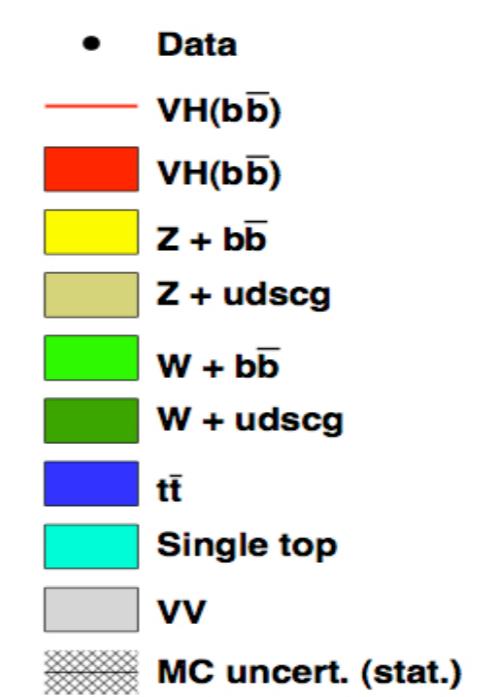
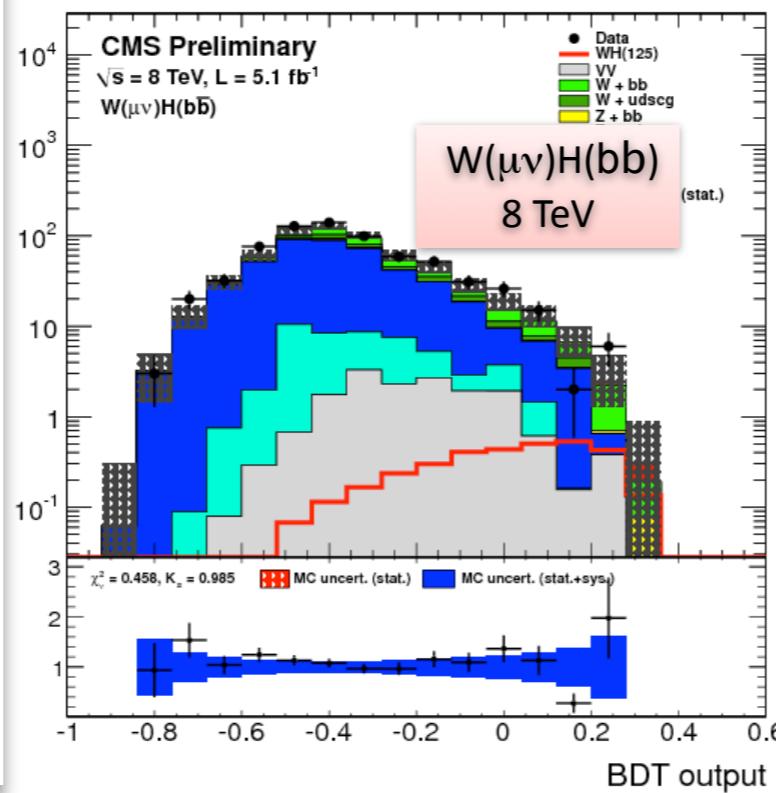
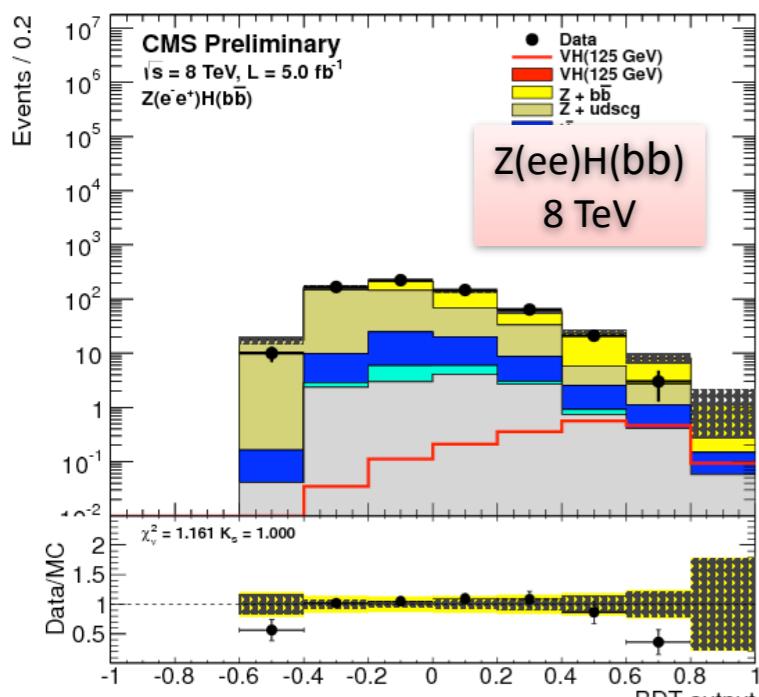
Boosted vector bosons:
 $p_T(V) \rightarrow 2$ ranges
2 b-tagged jets ($H \rightarrow bb$)
Back-to-back V and H,
reconstruct m_{bb}

Main backgrounds
estimated from data in
control regions (scales)



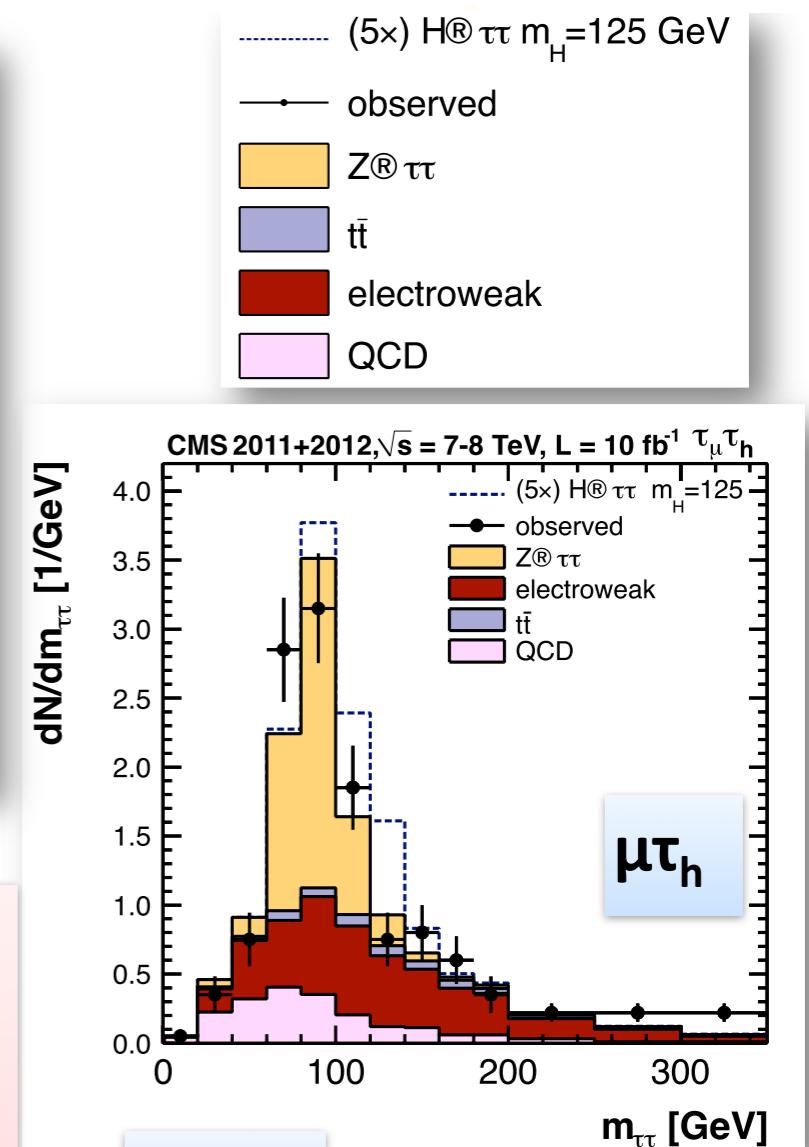
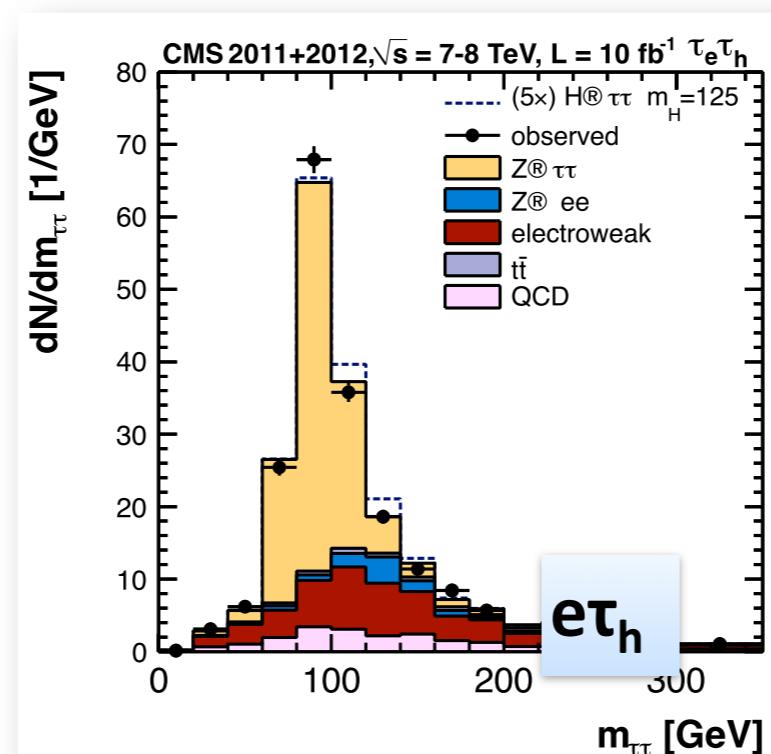
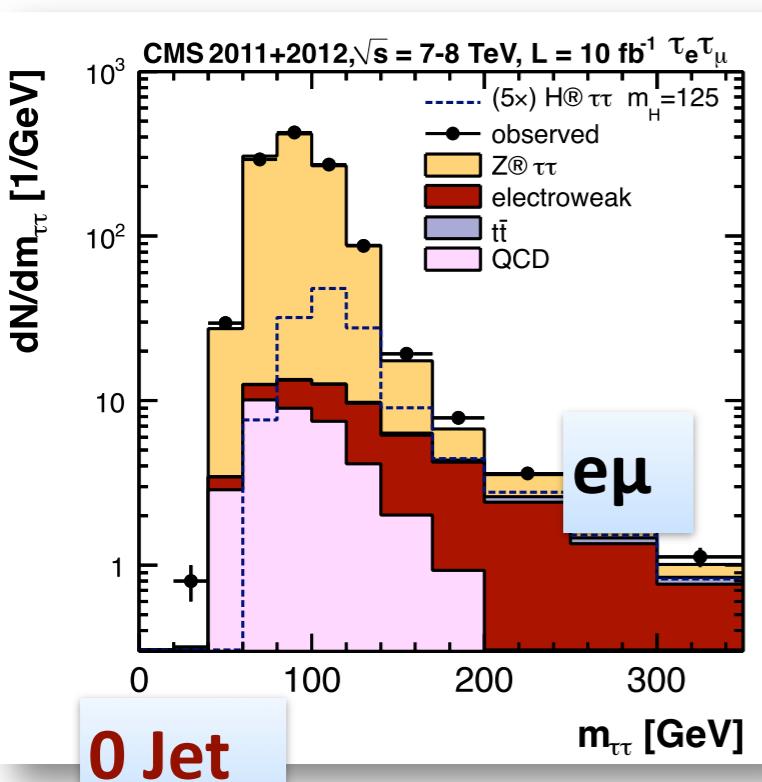
Examples of final MVA distributions

H->bb



$$H\rightarrow \tau^+\tau^-$$

Mass Distributions in Event



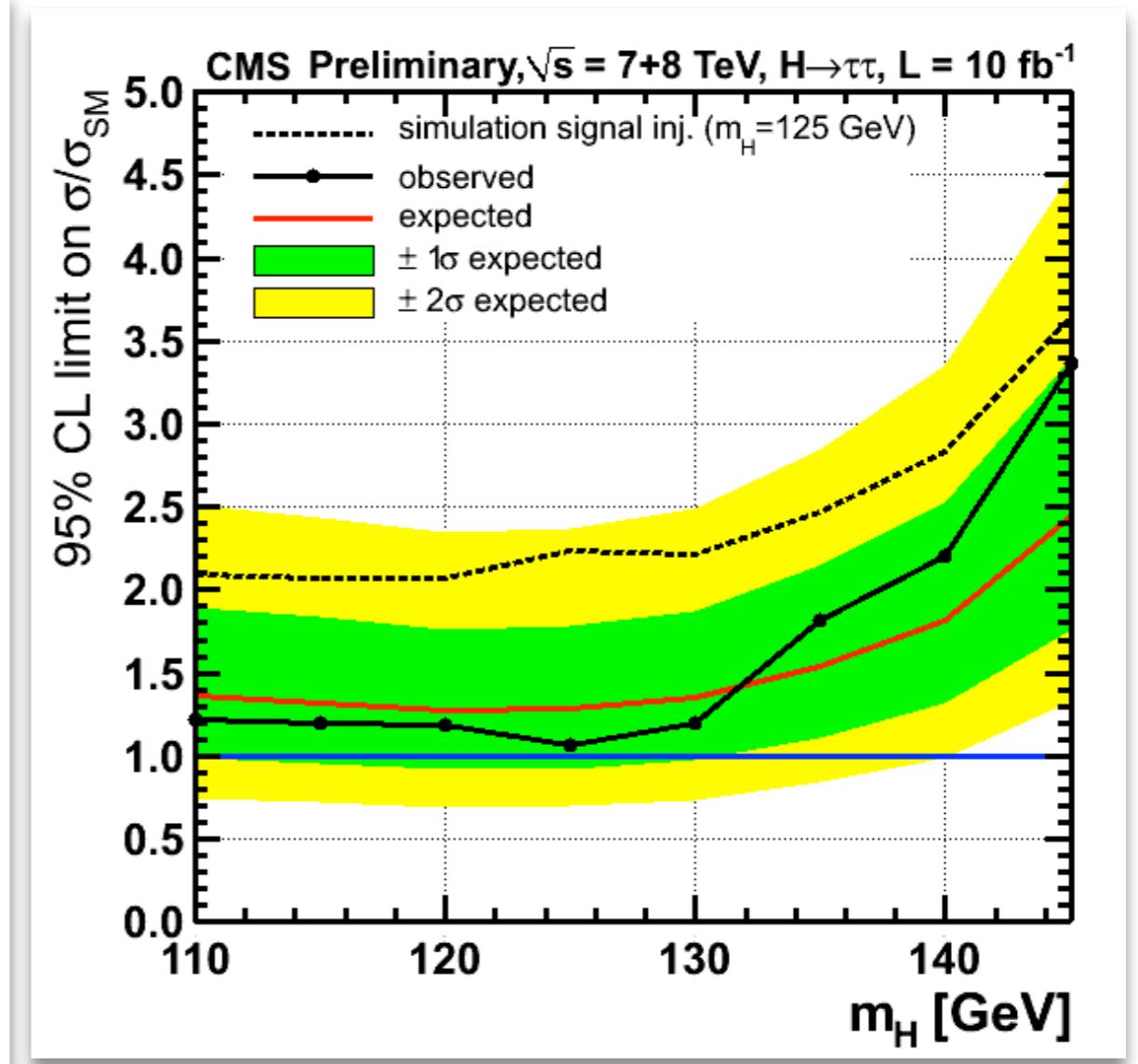
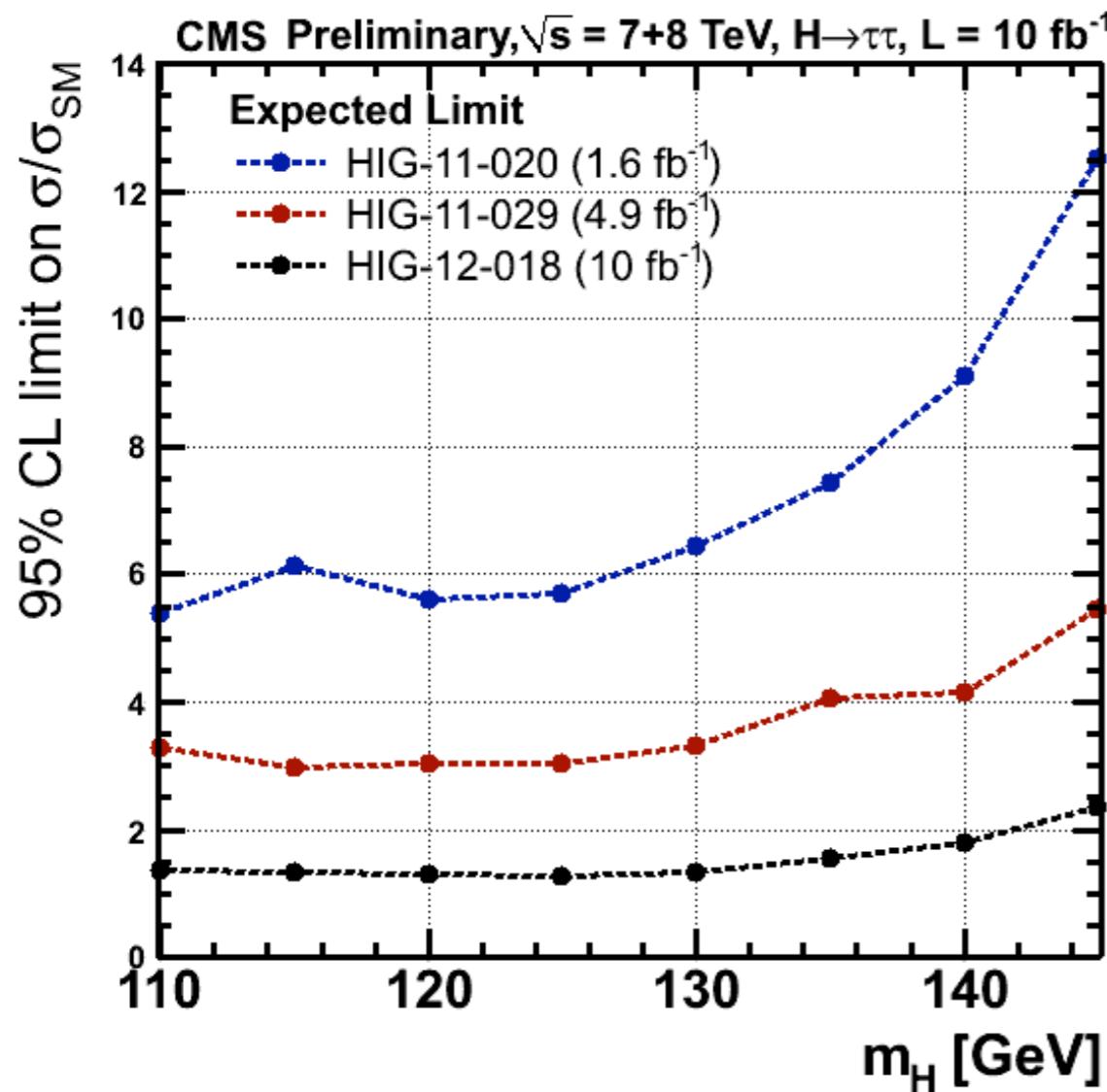
- Constrains energy scales and efficiencies
 - Large Drell-Yan background
 - Sensitivity boosted by low/high p_T split

4x5 channels

- Enhanced sensitivity to gluon fusion
 - Improved mass resolution
 - Sensitivity boosted by low/high p_T split

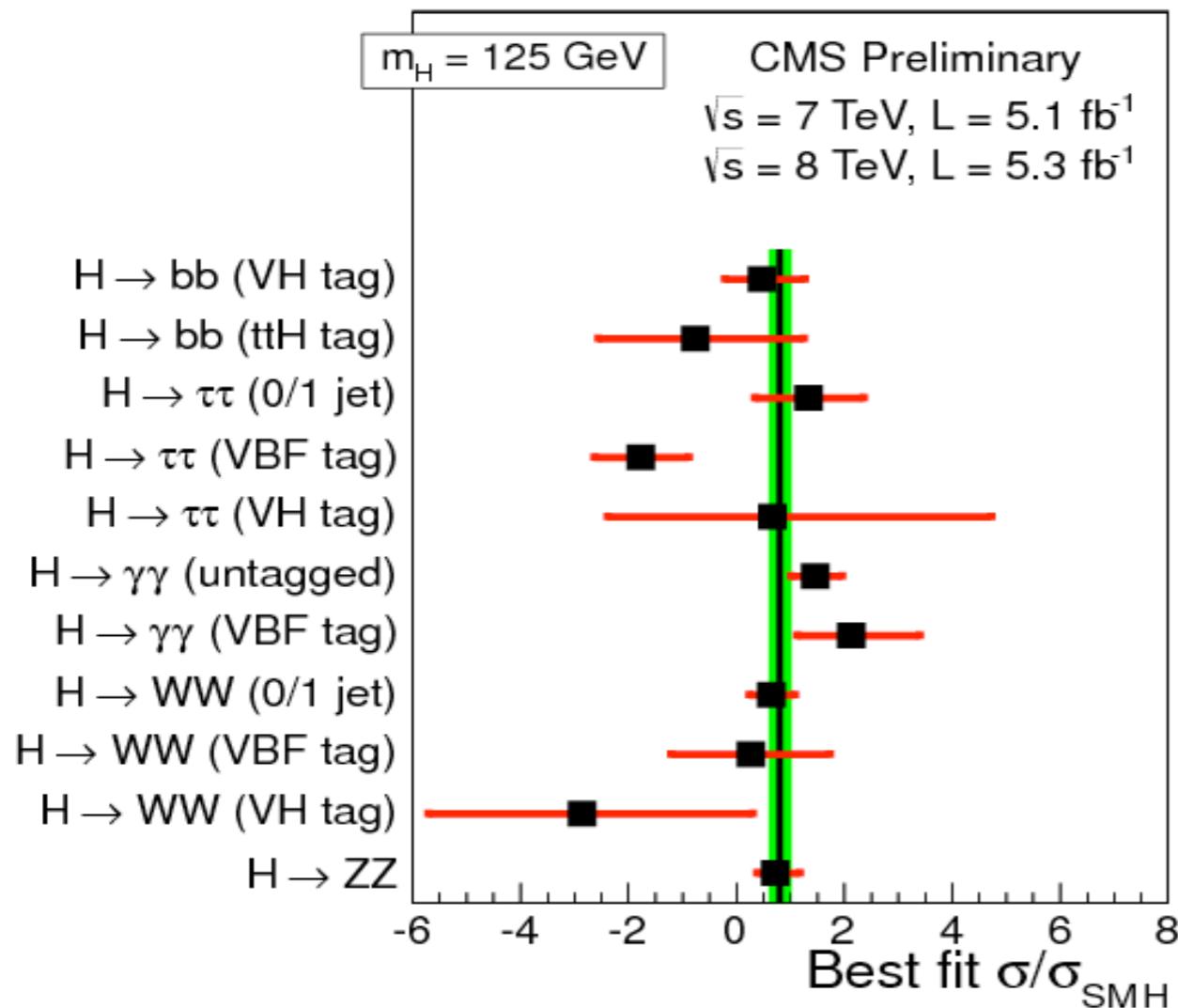
- Enhanced sensitivity to VBF production
 - Highest sensitivity for $m_H < 130$ GeV

Results for $H \rightarrow \tau\tau$

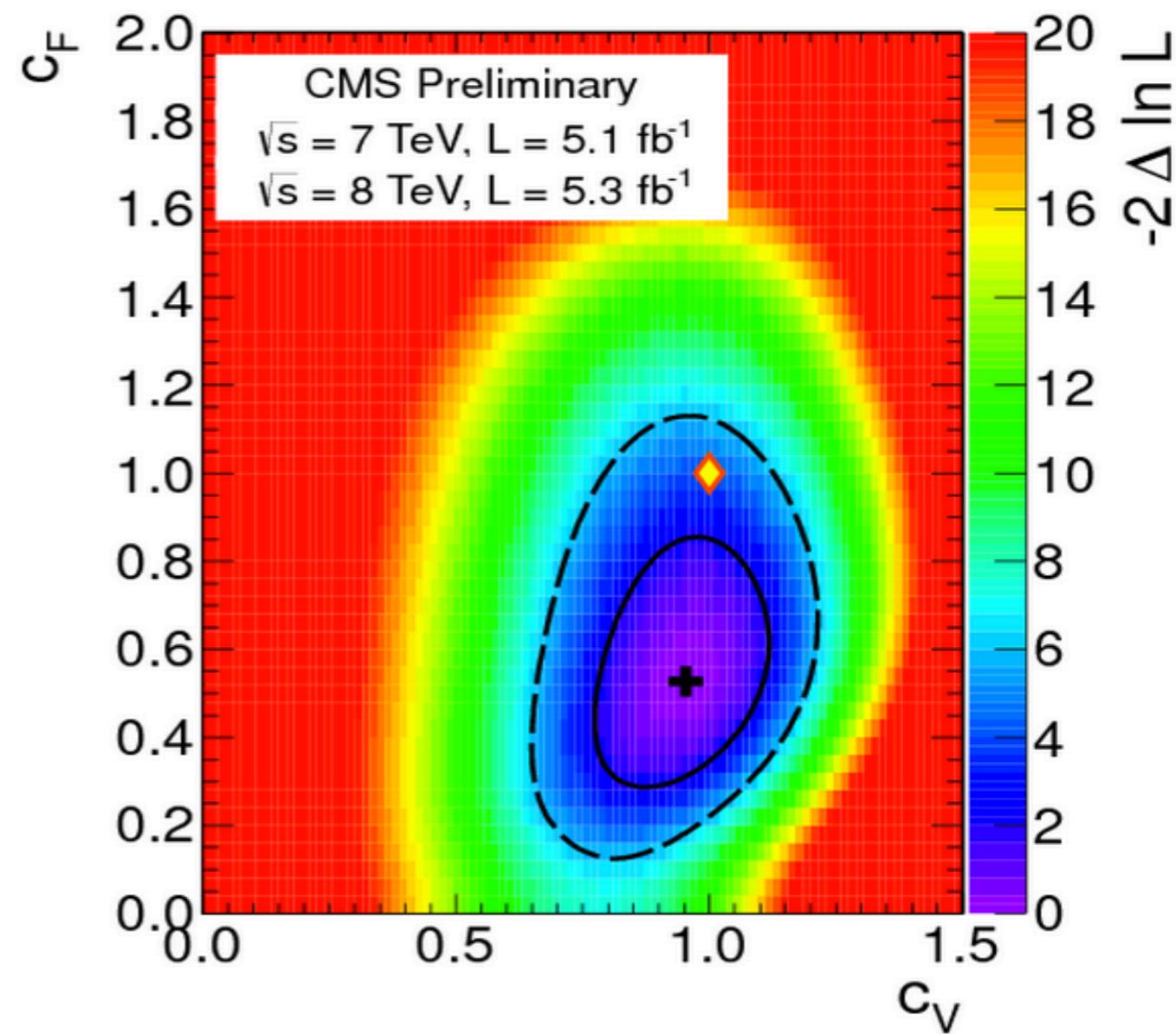


- ~2x improvement in sensitivity
 - => 70% improvement in sensitivity on the same data
 - 40% improvement with the additional luminosity
- No significant departure from SM background-only expectation
 - Observed limit of $1.06 \times \text{SM}$ at $m_H = 125 \text{ GeV}$ (expected 1.28)

Fit Boson and Fermion couplings



- In agreement with SM within 95% CL



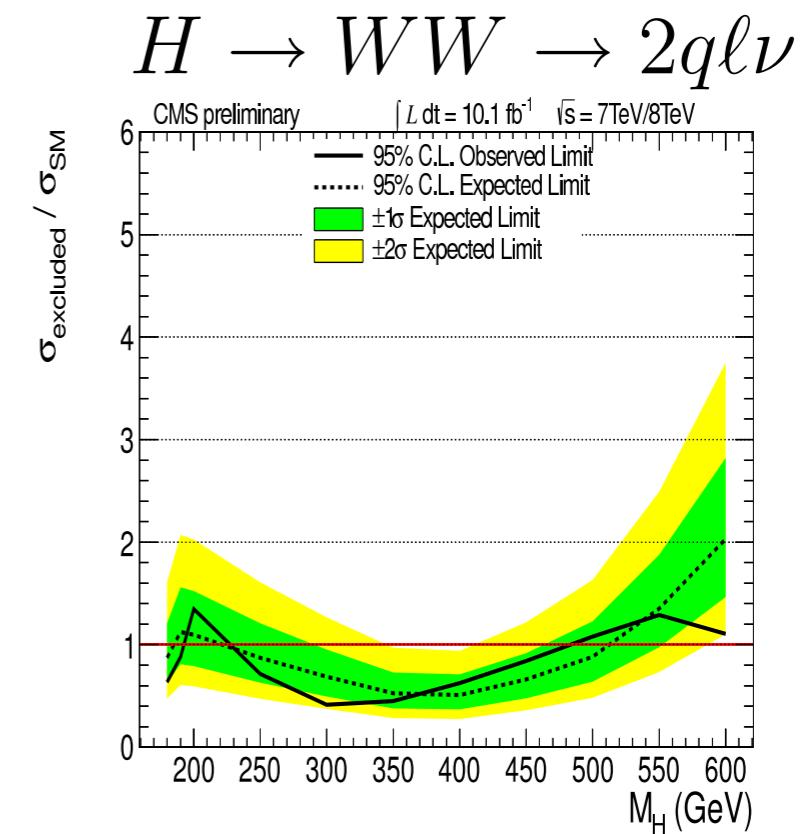
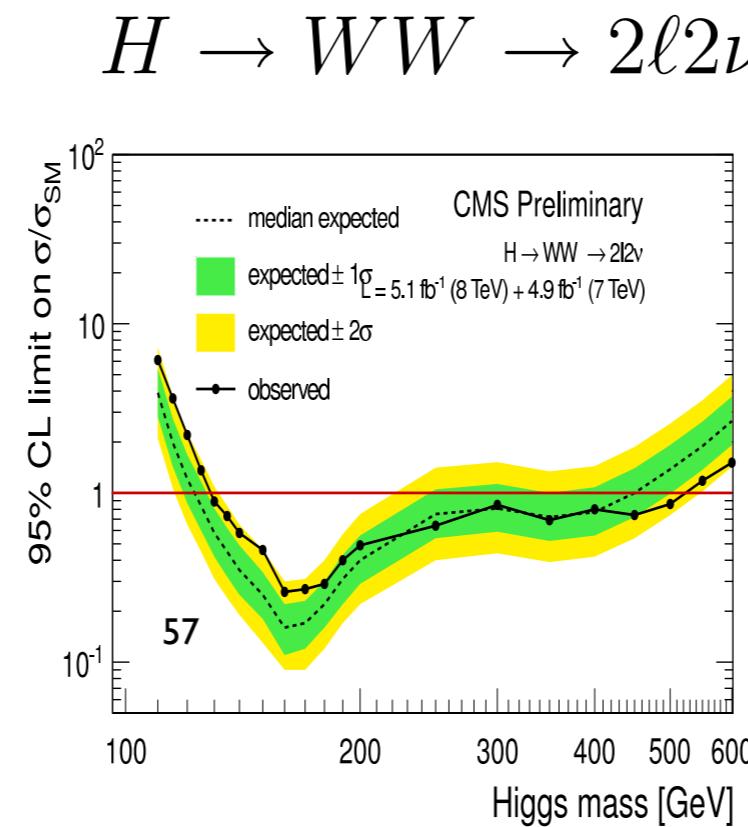
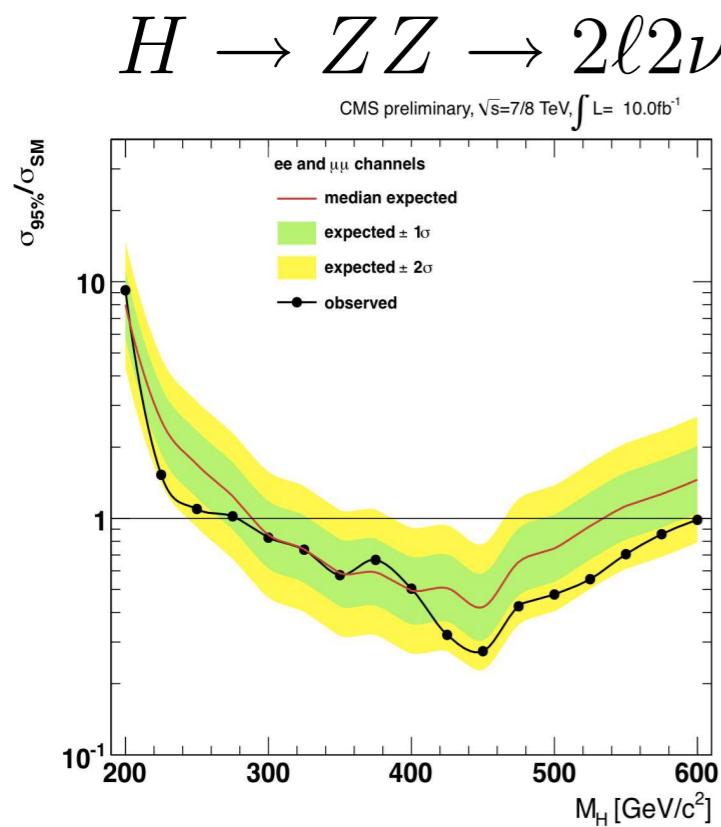
SM Higgs: High Mass

- Extensive effort across the full mass range:

$$H \rightarrow ZZ \rightarrow 4\ell, \quad 2\ell 2\tau, \quad 2\ell 2q, \quad 2\ell 2\nu$$

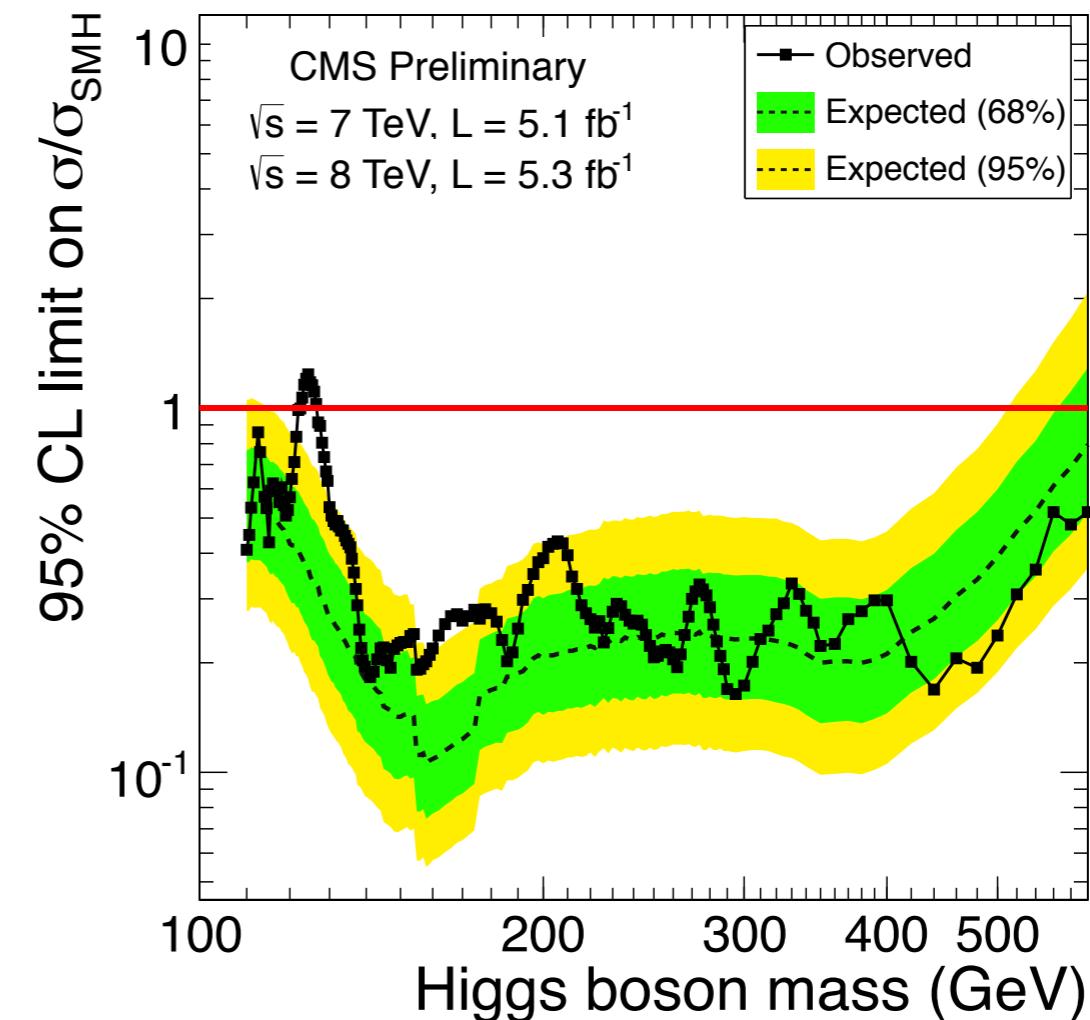
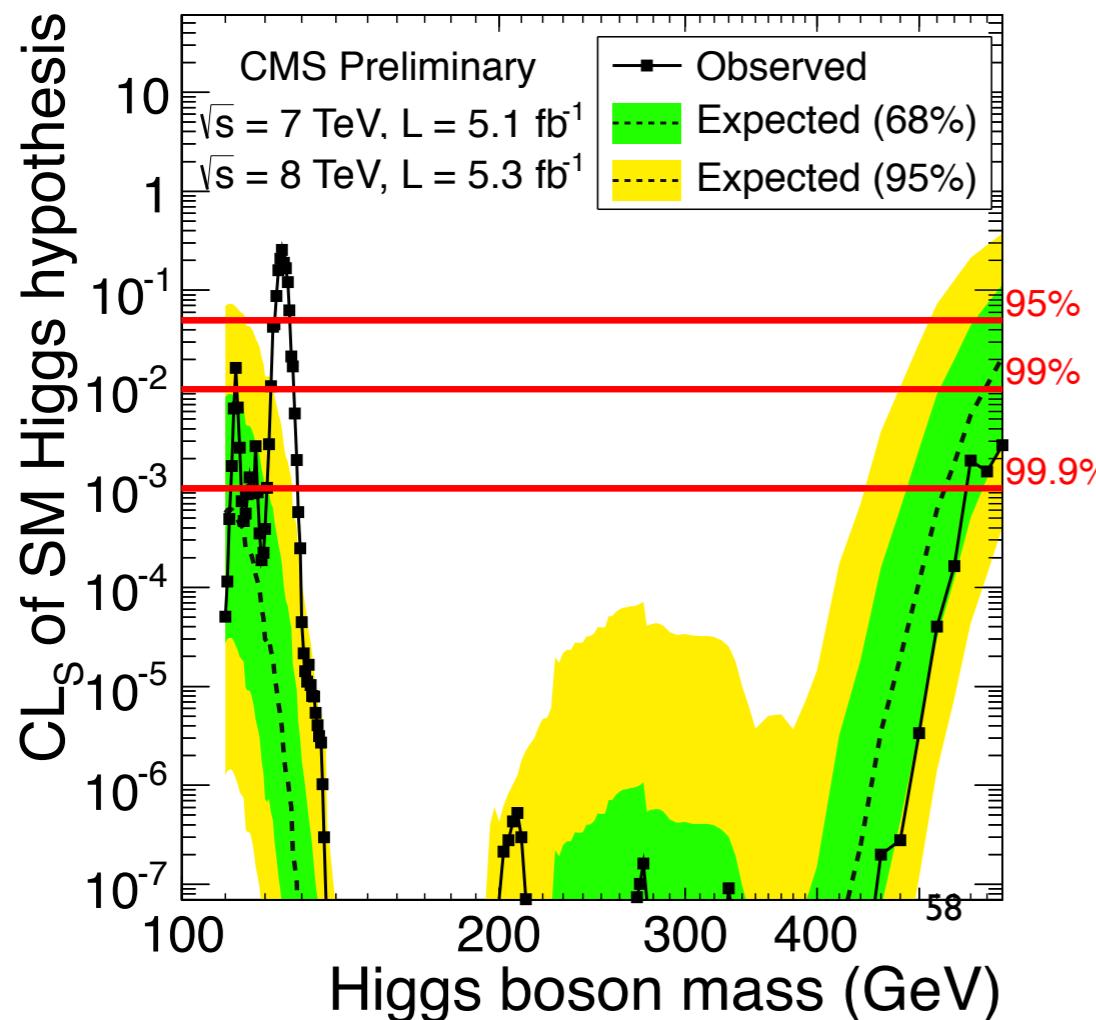
$$H \rightarrow WW \rightarrow 2\ell 2\nu, \quad 2q\ell\nu$$

- Recent updates:

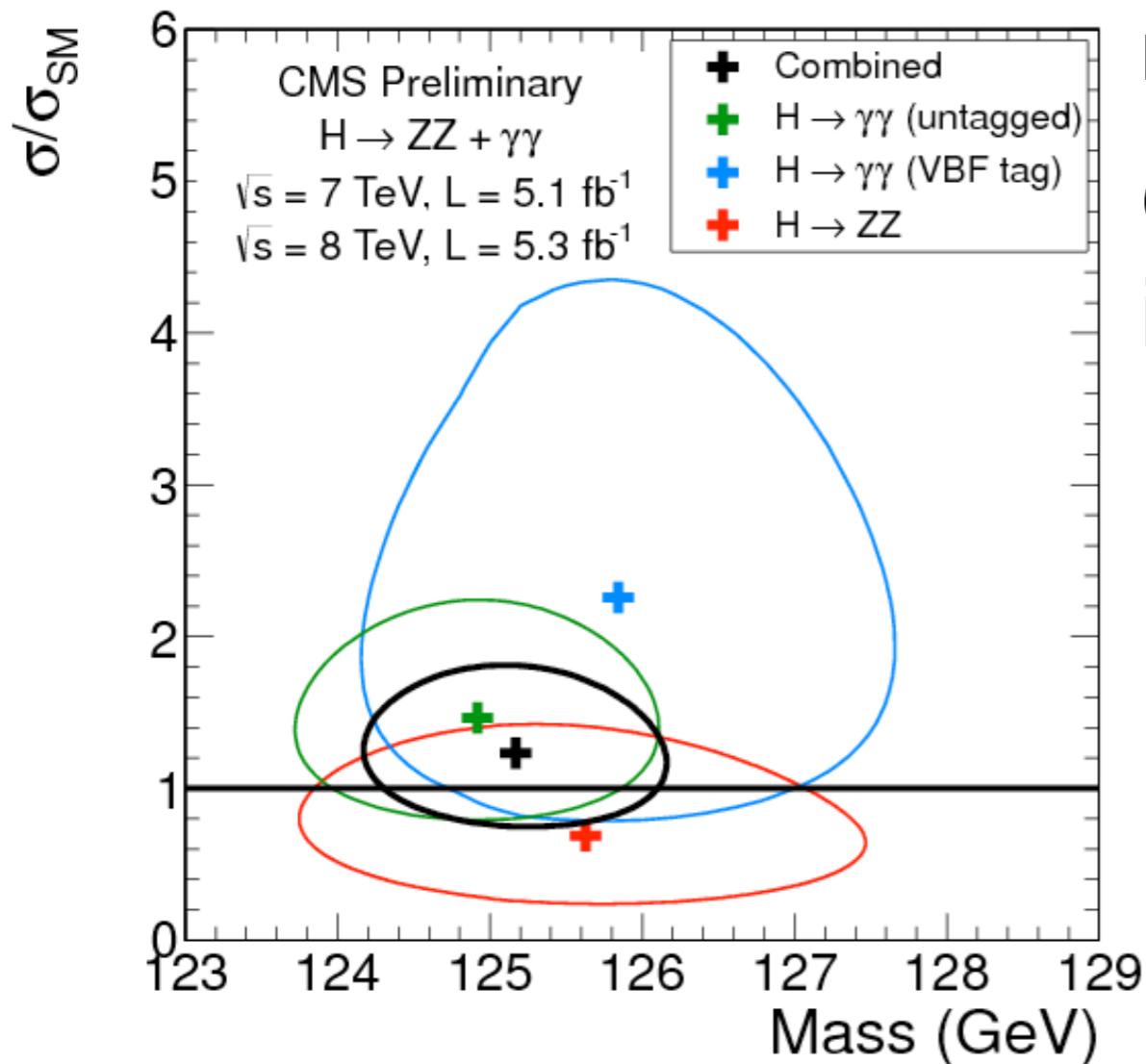


SM Higgs Exclusion

- Excluded SM Higgs in the full search range
 - except for a narrow range around 125 GeV



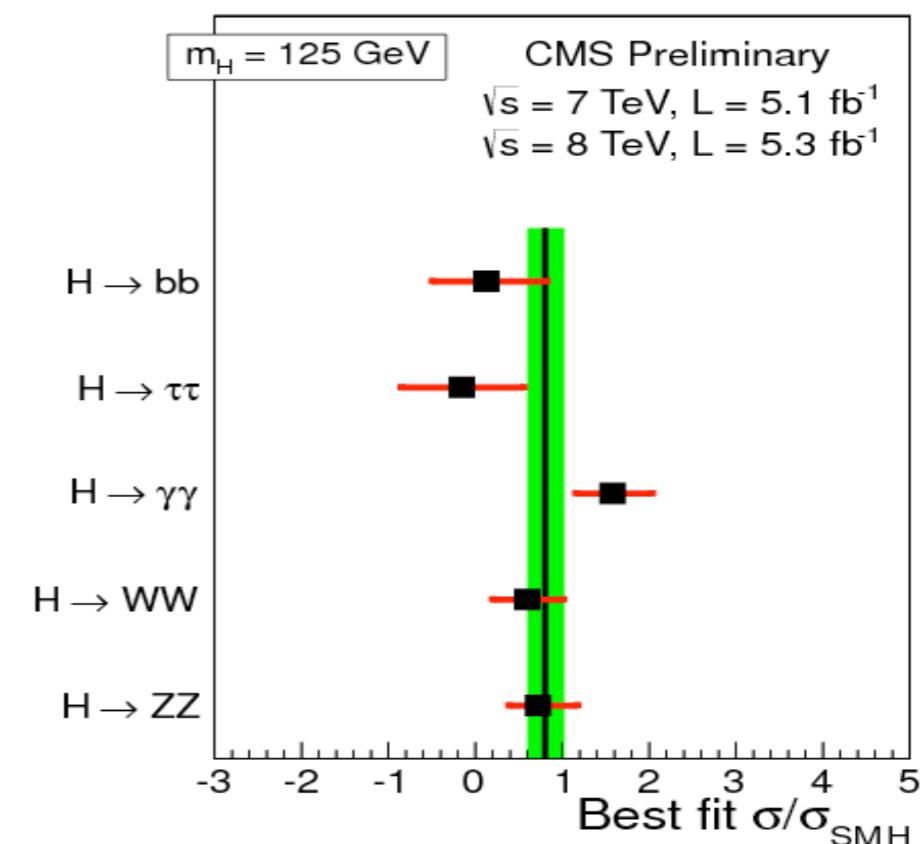
Characterization of the excess



The observed state has mass near $125.3 \pm 0.4 \pm 0.5 \text{ GeV}$

Overall best-fit signal strength in the combination:

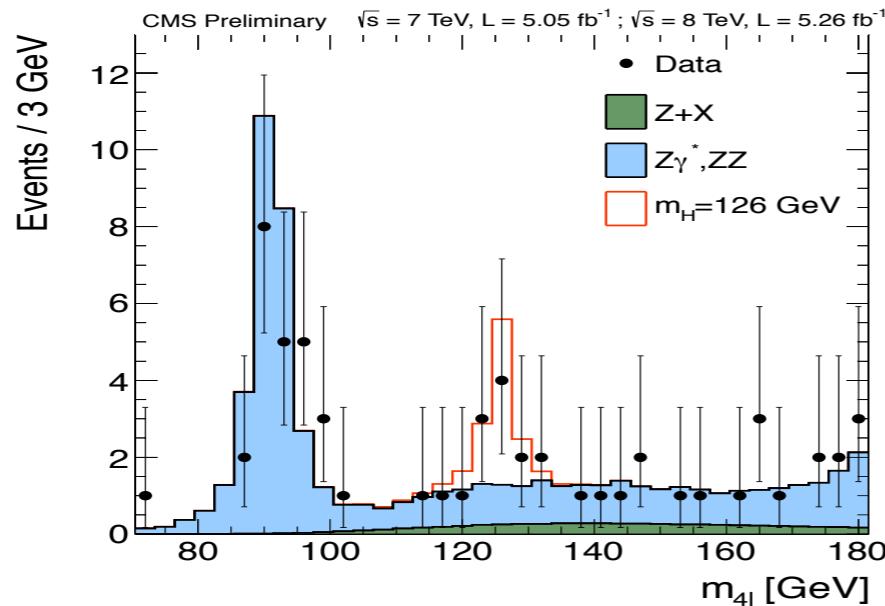
$$\sigma/\sigma_{\text{SM}} = 0.80 \pm 0.22$$



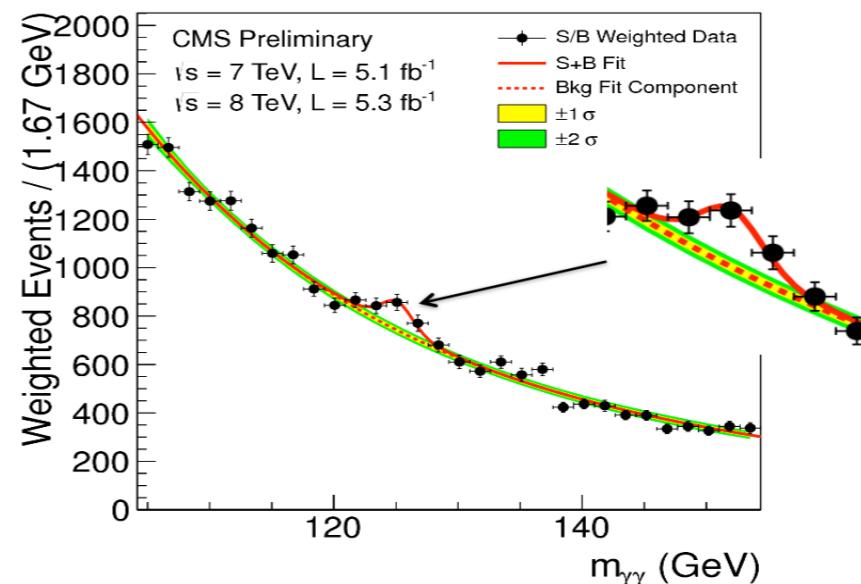
Observation of a New Boson

- Observation of a New Boson on CMS: 5σ excess

$$X \rightarrow Z^{(*)} Z^{(*)}$$



$$X \rightarrow \gamma\gamma$$



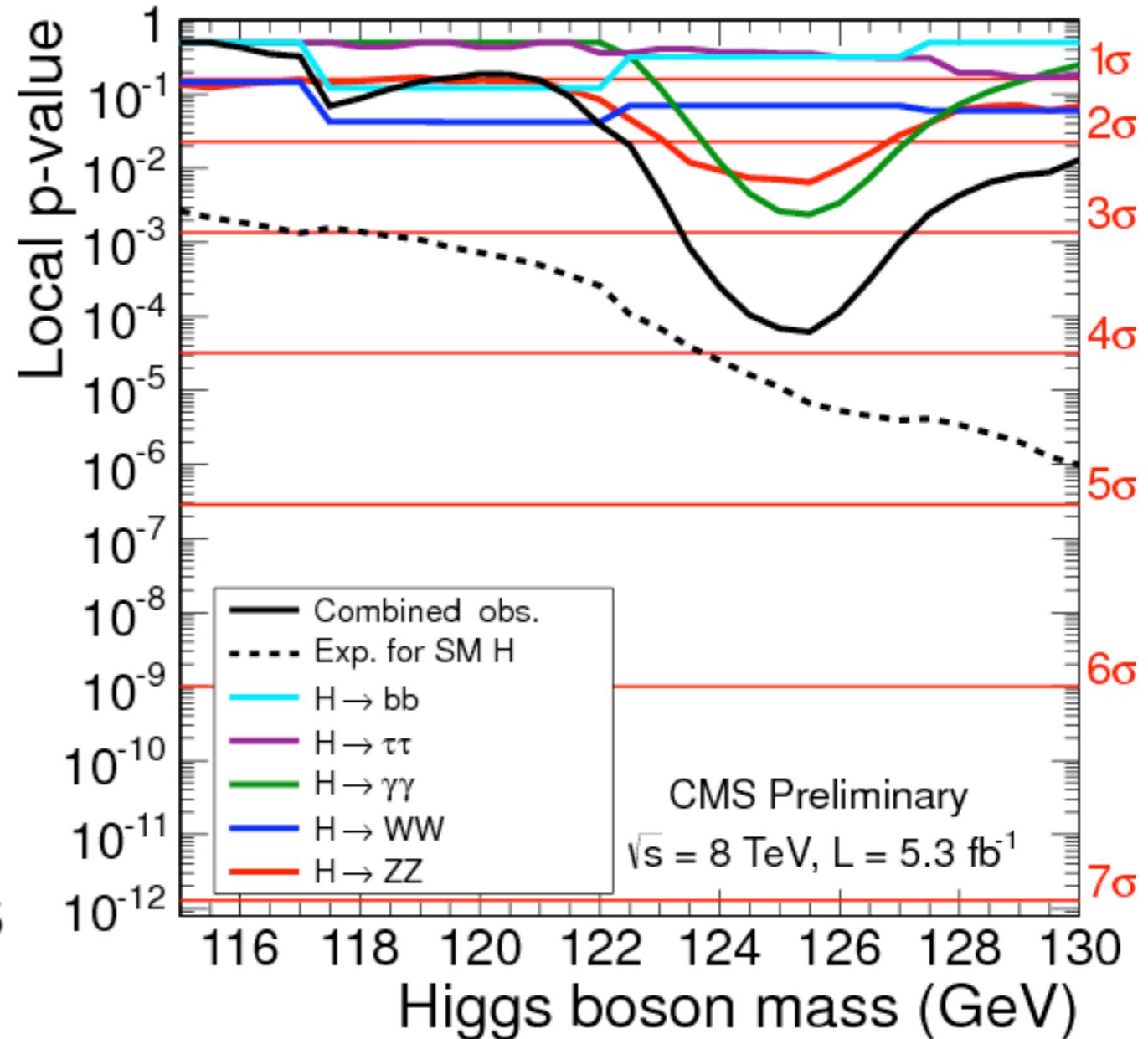
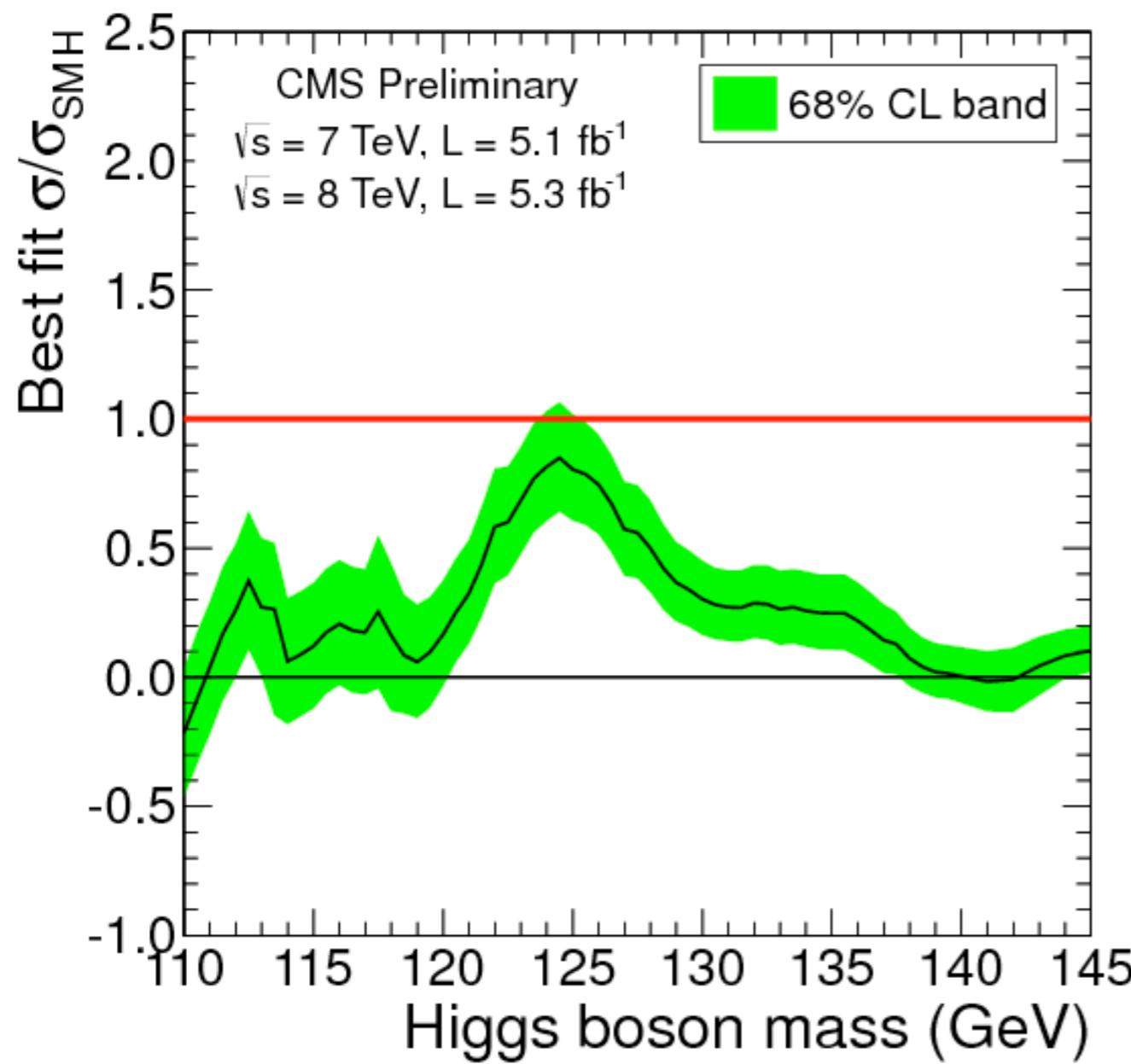
- What we know:
 - it is a **boson**, $\text{spin} \neq 1 \Rightarrow \text{spin} = 0 \text{ or } 2 \dots$ (nothing like this before)
 - it couples to **vector bosons**
- What we do not know:
 - if it is the **Higgs boson**, if couples to **Fermions** (matter)
 - expect it to be **elementary**, if not \Rightarrow even more interesting...
 - if it is a tip of an iceberg of new exciting states of **matter** / **energy**

CMS collaboration



BACKUP

All channels combined

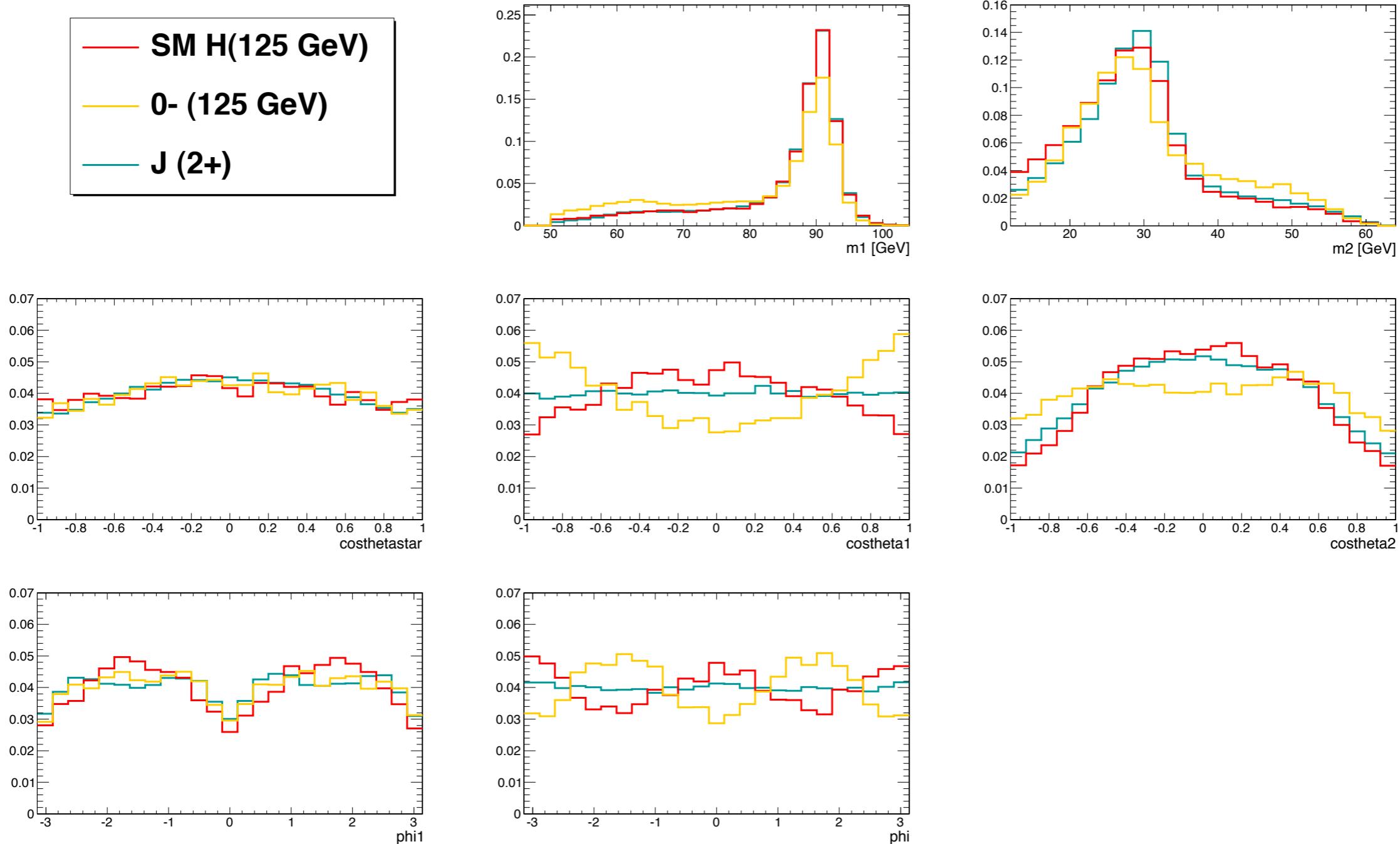


Angular / Mass Distributions

- The JHU generator: <http://www.pha.jhu.edu/spin>

See also ICHEP talk "Determination of properties of a Higgs-like resonance at LHC"

<https://indico.cern.ch/getFile.py/access?contribId=473&sessionId=53&resId=0&materialId=slides&confId=181298>



Amplitude for Spin-0

- Amplitude for $X_{J=0} \rightarrow V_1 V_2$ (see wine-and-cheese April 30, 2010)
<http://theory.fnal.gov/jetp/talks/gritsan2010.pdf>

$$A = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} M_X^2 + a_2 q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right)$$

$$A_{00} = -\frac{M_X^2}{v} \left(a_1 x + a_2 \frac{M_{V_1} M_{V_2}}{M_X^2} (x^2 - 1) \right)$$

$$A_{\pm\pm} = + \frac{M_X^2}{v} \left(a_1 \pm i a_3 \frac{M_{V_1} M_{V_2}}{M_X^2} \sqrt{x^2 - 1} \right)$$

$$x = \frac{M_X^2 - M_{V_1}^2 - M_{V_2}^2}{2M_{V_1}M_{V_2}}$$